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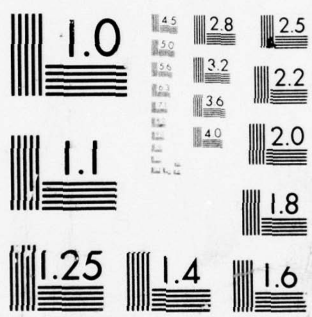

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4-6 NOVEMBER 1969

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The seminar proceedings contain 16 papers presented by Corps of Engineers employees on 4-6 November 1969 at The Hydrologic Engineering Center. The papers pertain to problems and techniques of reservoir systems analysis. Titles and authors of papers are as follows:

(see next page)

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Flexibility in Water Resource Management as Related to Reservoirs	David H. Halsey
Flood Regulation of Kansas River Basin Reservoirs	R. Terry Coomes
Operation Studies of the Kaskaskia River Reservoir System	William H. Pinner
System Operation of Reservoirs on the Apalachicola River	Richard A. Eckstine
Reservoir Operation for Conservation on Roanoke River	James W. Midkiff
Comparison of Pre-Construction and Post-Construction Reservoir Regulations	Warren L. Sharp
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PROCEEDINGS OF A SEMINAR

ON

RESERVOIR SYSTEMS ANALYSIS

The Hydrologic Engineering Center
Corps of Engineers
Davis, California

4-6 November 1969

FOREWORD

This seminar was held primarily to exchange information within the Corps of Engineers on problems and techniques of reservoir systems analysis, but also to define and illustrate these problems and techniques for the benefit of those endeavoring to advance the technology.

Presentations are, in general, frank evaluations by the authors and are not official Corps documents. The views and conclusions expressed are those of the individual authors and are not intended to modify or replace official OCE Engineer Regulations, Engineering Manuals or Engineer Technical Letters.

These documents indicate that simulation techniques have gained wide acceptance in the actual design and operation of water resource projects. While the application of advanced techniques of operations research has been precluded by the complexity of water problems, it is hoped that the explanation of problems presented will stimulate the greatly needed development of these techniques.

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SEMINAR ON RESERVOIR SYSTEMS ANALYSIS

INTRODUCTORY REMARKS

by

LEO R. BEARD, Director
The Hydrologic Engineering Center

I want to welcome you to The Hydrologic Engineering Center and to the beautiful city of Davis. We hope that this seminar on Reservoir Systems Analysis will be fruitful in describing the nature of reservoir systems problems to the profession and in stimulating interest and thought on your part that can be directed toward the solution of these problems.

Although the HEC has existed for more than 5 years, this is the first seminar of this type that has been conducted in the Center. Perhaps it would be of value to review very briefly the purposes and functions of the HEC and how a seminar of this type fits into our general program.

The Center has four basic missions: Research, Training, Methods Systemization, and Special Assistance. Research activities are directed toward the solution of problems that have developed in recent years because of the increased interest and activity in water resources development. I am sure that the presentations and discussions in this seminar will illustrate the extreme complexity of some of these problems, which are associated with the great diversity of hydrologic phenomena, economic factors, legal and institutional constraints, and social needs.

The Training program of the Center is intended to familiarize engineers throughout the Corps with the new techniques and to train the younger engineers in the traditional methods, as well as in the new techniques. This program is implemented primarily with a series of eight or ten formal training courses per year, each lasting about 2 weeks and covering a special area of hydrologic engineering. These courses are supplemented by individual training tailored to specific needs, as well as by seminars such as this.

The Methods Systemization program of the Center is intended to develop manuals, step-by-step instructions, and computer programs that can be readily used in each office for training as well as for actual design and operation studies.

The Special Assistance program provides consulting services on specific problems associated with authorized reports and projects in the various Corps offices. It is these special problems that instigate a good deal of the research and provide excellent means of testing the results of research and methods systemization work.

This particular seminar topic was selected, because the problems associated with reservoir systems studies are extremely complex and because new solution techniques show considerable promise but have not yet been demonstrated to apply effectively and generally to the many problems that exist. The gap between origination of new techniques and their implementation in design is not due, as many may think, principally to reluctance or lack of understanding on the part of the design engineer, but rather to the fact that the development process of applying new techniques to real problems is difficult and time-consuming. Consequently, a major objective of this seminar is to outline to the profession the real nature of these problems, so that application of new techniques can be facilitated.

The range and complexities of reservoir systems problems will be amply demonstrated in the presentations to be made and in the accompanying discussions. We have only to consider a few features of reservoir systems studies to appreciate the complexity of problems involved.

- There is a need to maintain storage in a reservoir system during wet periods for use during subsequent droughts, and yet some space must be maintained empty during wet seasons for flood control, if this is a project function.

- There is usually a need to release water during the summer for irrigation and other purposes, when it is desired to maintain full reservoirs for recreation and power head.

- Water for different purposes is needed at different times during the year and at different locations, but these different needs might or might not be served by the same water, depending on time and location.

- Water needed for power and water lost through evaporation are non-linear functions of the state of the system, and actual quantities cannot be specified accurately in advance.

- The best choice of releases from alternative reservoirs that can supply a given demand is a complicated probabilistic function of future inflows and demands, as well as of the state of the system.

• Even in small systems, the number of reasonable combinations of rule curves for planning and operation studies and the number of reasonable combinations of reservoir sizes, project locations, powerplant capacities, outlet, channel and diversion capacities, etc., for planning studies are so great as to prohibit a systematic examination of all alternatives.

• Any thorough study of system design or operation must be based on many years of data and, if possible, on hundreds of years of synthetically generated events. Yet, some project features, such as flood control and power, need be examined on a short-interval basis, such as hourly. The combination of these two requirements demands either a great deal of ingenuity or tremendous amounts of computation.

• Even when an acceptable objective for design or for formulation of operation rules can be developed, the evaluation of some functions such as recreation, fish and wildlife preservation, and quality control, and evaluation of the adverse effects of short-term water shortages can be challenging and can require great quantities of basic data.

Techniques now employed in the solution of these problems are generally inadequate in comparison with the importance of accurate solutions. In general, it is possible to simulate the operation of a system through a given period of time with specified inputs and demands. There are many approximations made in these simulation processes, but acceptable accuracy is usually obtainable. However, in some complex systems, simulation is taxing the present technology and computer capability.

Operations research techniques, such as linear and dynamic programming, have been rarely implemented in the actual design and operation process, although they have been applied to relatively simple segments of these problems, principally supplementary to traditional procedures. Attempts to apply operations research techniques have been hampered principally by the necessity to simplify problems to suit the techniques and by the dimensionality problem, which results in prohibitive amounts of computation.

The purposes of this seminar are to provide statements of specific problems in reservoir systems analysis that face the Corps of Engineers today, to describe the solution techniques that are currently implemented, and to discuss the potential development of the technology, particularly the applicability of operations research techniques. I hope that each of you will keep these points in mind as you make your presentation. We hope

that, while you are here, you will become acquainted with the staff at the Center and with the work that we are doing. If there is any way that we can help in regard to your accommodations or travel or other matters while you are here, please let us know.

STATUS AND POTENTIAL OF RESERVOIR
SYSTEMS ANALYSIS

by

A. J. Fredrich[1]

During the past decade there has been an unparalleled increase in technology associated with water resources development in the United States. Some of the increased technological capability must be attributed to natural response to the stimuli that are produced by an ever-more-aware society reacting to the many facets of a national program that has been in existence for a hundred years, but which only recently has received national attention. However, the greatest increase in technological capability has occurred as a result of the emergence of the electronic computer as an important tool in planning, analyzing, and operating water resources systems.

The engineering profession has made important strides in adapting yesterday's techniques to the computer for solution of today's complex problems. However, in many instances we are finding that yesterday's techniques are inadequate for solving today's problems, even with computers, because the problems themselves are becoming increasingly complex. Therefore, we cannot rely solely on finding faster and more economical ways of applying techniques which worked well on the problems of ten years ago, because when the fastest and most economical application is developed, it may produce answers which are not complete or which are irrelevant. Since our expectation is that the problems associated with water resources development in the future will be even more complex than they are today, we must surmise that the promise for tomorrow lies in developing and using techniques that eliminate the shortcomings of existing methods, fully utilize the computational capability of the electronic computer, and produce solutions that are responsive to a broad range of existing and future requirements.

Our success in developing these new techniques is dependent on how well we use what we have learned thus far about planning and operating reservoir systems, on how well we are able to implement mathematical methods that promise solutions for some of the more complex problems, and on how effectively we are able to integrate this technical knowledge and these mathematical methods into techniques which are designed to exploit the capability of the computer as an engineering and management tool. A look at the problems and methods of solution from the past and in the present may help us realize what we know, how we learned, and where the problems of the future may be.

Reservoir systems as we know them now - a group of reservoir projects operated collectively to serve several purposes (which may be specified for individual projects and for the system as a whole) did not, as a rule, come into being as a planned entity. In most cases, projects were planned,

[1] Chief, Training and Methods Branch, The Hydrologic Engineering Center

designed, constructed, and operated as single units to serve one or more purposes, with little or no consideration being given to projects in nearby basins or in the same basin. It soon became apparent that there was a need to consider the operation of existing projects when planning a new project; but in most instances this consideration was limited to accounting for the operation of the existing project or projects as originally designed, rather than a complete reevaluation of all projects, including the new addition. The result of this type of analysis was that each component was planned and designed to function as efficiently as possible within the limitations imposed by operation of existing projects. Reanalysis of all projects with the addition of each component was often impossible because of the time required to perform operational analyses by manual methods. Some relatively small systems were visualized as systems from the very first, and coordinated operation plans for the system were devised at the time of its inception. However, the individual components sometimes suffered under this type of planning because of the lack of an interim operation plan that made allowances for the differences in operation of the individual components during the time between development of the first project and completion of the system.

Because systems developed in these ways and because the needs and interests of the populace changed as time went on, it was recognized at some point in time (which varied according to the importance of water resources development in the given area) that a collection of reservoir projects existed in a given basin or area, and that these projects were being operated under a hodgepodge of criteria for a remarkably wide variety of purposes ranging from vector control to flood control. As purposes other than the originally authorized purposes were included in the operation of these projects without complete restudy, it was not unusual for the existing operation for a single project to be a conglomerate of partially defined criteria which were sometimes in conflict with one another. Even more frequently, the operation at one project for one purpose was found to interfere with the operation for another purpose at another project in the basin, and in some limited cases it was found that strict observation of operating rules at several projects would have them operating in direct opposition to one another for some purposes.

With these realizations came the development of coordinated hydrologic studies for operation of reservoir systems for all authorized and approved purposes. These studies attempted to account for the temporal and spatial variation of hydrologic conditions within a reservoir system during a historical period of record and to define operation criteria that would enable the system to satisfy both individual project and system demand for all purposes under these conditions. Though accomplished manually, some of these studies were remarkably detailed, taking into account most of the physical and hydrologic conditions which could be expected to influence the operation of the system. The primary shortcomings of these studies were in the specification of interactions between components in the system and in

the establishment of bases for operational decision-making in instances where there were conflicts among purposes or where a demand could be satisfied by combinations of releases from more than one project. Despite these problems, however, these studies were a significant step forward in the evolution of reservoir systems analyses, for it was at this time that the concept of a system was established and the benefits of system operation began to be identified and realized.

As soon as the benefits of system operation were quantified, the next step of development in reservoir systems analysis was initiated. This step consisted of improving upon the basic system operation plan, and progress in this area was limited by two factors: (1) The amount of time, manpower, and money required to make an analysis, and (2) the problems in quantifying the many intangible and nonmonetary purposes for which a system is operated. At about this time, the use of electronic computers began to be considered for reservoir systems studies. The first attempts to adapt reservoir systems studies to computers consisted primarily of programming the computers to do precisely what was done by hand. This, of course, built into the computer analyses the same problems and shortcomings which existed in the manual analyses. Thus, a major problem - that of time, manpower, and money - was attacked and largely overcome, but serious deficiencies still existed. In almost every case, these first attempts at computer utilization were limited to analysis of a specific system at a specific state of development, with specific operation rules of very limited flexibility. Besides failing to solve several critical problems inherent in manual methods, these models were very difficult to modify to account for changes in system components or operating rules. These models were, however, excellent tools for evaluating the response of a given system with fixed operating rules to a variety of hydrologic conditions, and evaluation of the output from these models was an important factor in the development of better models, more refined operating rules, and in identifying parameters for which quantification would be necessary in improved analyses.

The next important step in reservoir systems analysis was the development of digital models which were generalized in the sense that they could be utilized for any configuration of reservoirs in a system, operating for any purpose, under a variety of possible operation rules. The primary advantage of these models is that changes in components or operating rules do not require expensive, time-consuming modifications of the basic model, and therefore, the effect of such changes can be rapidly and effectively evaluated. In most instances, these models are characterized by incorporation of relatively flexible operation rules and by use of computational techniques that differ significantly from those employed in manual analyses. Several of these models will be discussed in detail during this seminar. It would appear that the major drawbacks of this type of model are: (1) The requirement for large computers that are not always readily available to all potential users, (2) the amount of data required, (3) the difficulty in obtaining and processing the data for use in the model, (4) the inherent

complexity of a generalized model and the associated difficulty of describing the model and its data requirements to a potential user, and (5) the lack of techniques for systematic analysis of the voluminous output from the model.

These generalized models have been used in planning and design studies as well as in operation studies. The emphasis upon comprehensive basin planning makes an evaluation of an existing system an absolute necessity before serious consideration of additional projects in the same basin can begin. In this type of analysis the existing system is studied to establish a base condition in the basin, and each proposed project is then studied with the existing system to determine the effect of the new component on the system. In cases where several potential new components are being considered, they may be analyzed in groups or one at a time, with the existing system, as a screening procedure. After the screening analysis is complete, the entire system - existing projects and survivors of the screening - would be analyzed as a unit. Another type of planning study in which a generalized model can be used occurs where there are no existing projects but many potential reservoir sites. In this situation, the generalized model is used, often with generalized physical and hydrologic data, to study the influence of projects and combinations of projects on planning objectives. A third type of planning application for systems analysis is the study of staging of projects in a long-range plan.

Operation studies stimulated the development of computer techniques because of the almost continual need for reviewing and updating an operating plan for a system. Even a system that is not changing physically must be reanalyzed periodically because of the dynamic nature of changes in water use and because of changes in legal and social constraints which influence operation rules. The purpose of operation studies is to develop for a reservoir system operation rules that will produce a coordinated operation for each project - an operation which fully considers the interaction among the many purposes, the various component reservoirs, the relative priorities of the purposes, the physical limitations of each component, and the hydrologic conditions at each important point in the basin. These studies can be accomplished with varying degrees of complexity depending upon the given purpose of a specific study. In general, studies that are made to compare the effect of changes in operation criteria or the effect of changes in priority for one or more purposes must reproduce the response of the system with a high degree of fidelity in order to facilitate the detection and evaluation of all significant aspects of the change. Other types of reservoir system operation studies, such as filling studies, studies to develop short-term operating plans, and studies which have only limited objectives do not always have to be as detailed as the previously mentioned studies, and consequently the degree of fidelity of reproduction of the system may not be as important in these cases.

The use of stochastic hydrology in both planning and operation of reservoir systems has become increasingly important because of the relative

ease with which the stochastic data can be evaluated in reservoir systems simulation models. Because of the influence of sequences of hydrologic events on operation decisions and because of the ability to generate many different sequences of stochastic data, the use of stochastic hydrology can be a most significant factor in the development of operation criteria that are not unduly biased by the historical sequence. Likewise, planning decisions can be strongly influenced by the particular sequences in historical data, and therefore, the use of stochastic hydrologic data in system planning studies can, in some instances, produce marked improvement in a plan.

The most promising area for future development in reservoir systems analyses techniques is the type of analysis which includes linear, nonlinear, and dynamic programming and other types of mathematical optimization techniques. These techniques have been used on numerous relatively simple problems to demonstrate the nature of the method and the power of mathematical optimization. However, at this time it appears that most practical problems require consideration of too many factors, and consequently, the problems of dimensionality become limiting conditions. Also, numerous simplifying assumptions are frequently necessary to make the real-life problem fit the mathematical model, and the effect of these assumptions on the optimal solution and its relevance to the actual problem is difficult to ascertain. Despite these problems, it now appears that this type of technique must ultimately be utilized if optimal solutions to complex water resources systems are to be found.

A major problem that limits the usefulness of currently available simulation models is the problem associated with acquisition and verification of basic physical and hydrologic data. In the past, months were spent gathering and checking data for a manual system analysis, and it was not considered unreasonable, because the analysis itself was very time-consuming. Now, however, analyses can be performed at the rate of several per day and the tendency is to spend less and less time checking and documenting the basic data. This is false economy, because many errors can cause significant alterations in the final results - alterations which may not be discovered unless detailed evaluations are made of the input and output for each analysis.

Another similar problem in today's methods is the necessity for developing better methods of summarizing, analyzing, and documenting the results of an analysis. As is the case with input, the tendency today is to spend less time analyzing and documenting a particular analysis, and this is an invitation to trouble that can result in questioning the validity of all analyses made by computer.

Other problems associated with currently available techniques include the need for education of many individuals at policy-making, administrative, supervisory, and working levels; the need for access to the largest and

fastest computers; the need for new technical criteria (because new methods are pointing out new problems which were not encountered in older methods); and the need for development of methods for analyzing nonmonetary functions, which are becoming more and more important.

Success in overcoming the above problems will help maintain the status of simulation models as a primary tool in reservoir systems analysis. Concurrent progress in adapting mathematical optimization techniques to practical problem will insure that these techniques, coupled with the improved simulation models, will provide the engineer with the tools necessary to solve most problems in reservoir systems analysis in the foreseeable future.

SUMMARY OF DISCUSSION

Compiled by F. K. Duren[1]

For the most part, this discussion was devoted to the broad topic of optimization studies. Five more or less distinct subtopics evolved during the discussion. These subtopics were: (1) The definition of "optimum," (2) the difficulties of making and implementing a meaningful optimization study, (3) the relation of optimal designs in planning studies to optimal designs in operation studies, (4) the "seat-of-the-pants" approach to optimization studies, and (5) the future direction of optimization studies.

The discussion that was centered around the definition of "optimum" interestingly brought to light the fact that even among those making optimization studies there is disagreement over just what is meant by optimum. Of the several definitions offered, the one which met the greatest acceptance was that optimum meant "the best we could do with the data and methods of today." However, disagreement was voiced to this definition by one of the participants who maintained that optimum means the best solution that could ever be developed - a plan that could never be second-guessed.

Several other thoughts on what optimum meant or implied were presented by other participants. Mr. Fredrich pointed out that he had not intended to imply that an optimum plan was static but that changing economic conditions made it necessary to continually update an optimum plan of operation. It was also noted that there is a difference between the optimum policies developed by the academic and practicing professions. Since the practitioners are concerned not only with simulating the physical world but also using their results to operate a system, they are sometimes not able to accept every assumption that academicians may make in their studies. Hence, the optimal plan developed for a specific reservoir system by an academician could very well be different from the practitioner's optimal plan. Along this same line of thought, Mr. Beard pointed out that the academician tended to feel that the worth or accuracy of a practitioner's optimal plan was measured by its closeness to the optimal plan developed by the academician.

A greater part of the discussion was devoted to the difficulties of making and implementing a meaningful optimization study than to any other subtopic. Much emphasis was placed on the dependence of an optimization study on the reliability of the input data. Mr. Halsey thought that a prohibitively expensive fine-grid network of recording stations would be

[1]Graduate Student, University of Nevada, on fellowship with The Hydrologic Engineering Center.

necessary to implement real-time computer operation of a reservoir system. Mr. Lewis stressed that since we cannot always be sure of the quality of the input data, we cannot be sure of our optimum solution.

Another point of discussion was whether a consensus of opinion should be reached on what is the optimum plan. Mr. Lewis maintained that it is not necessarily true that a consensus of all interested parties will be reached on one optimum plan. Mr. Fredrich also suggested that frequently there is no one person or group of persons who is allowed to specify that an operating plan is optimal in a real-life situation. Because many people and many interests are affected by the actual operation of a system there will be many different "optimal" plans - often as many different "optimals" as there are interests. Furthermore, the problem is compounded because the various interests may not have a common basis for communication or for comparing their "optimal" needs to the needs of other interests. Consequently, the optimal real-time operating plan may be the plan that minimizes the discontent among the various interests. However, it was mentioned that possibly a consensus could be reached on one optimum plan provided there was agreement on what were the constraints on the system.

A particularly sensitive topic was the implementation of the optimum plan once it had been developed. Mr. Fischer suggested that the administrative problems associated with obtaining approval and implementing a new policy of operation can be very challenging. Several participants thought that implementing an optimal policy was much more difficult than developing the policy.

Mr. Beard raised the question whether it was difficult for the Districts to accept newer methods of computer solutions or to update their older techniques. In response, Mr. Clare stated that the constraints on a system limited the flexibility in adopting new techniques to solve old problems. He thought that since, in most cases, the constraints could not be radically changed, it would be very difficult to start a completely fresh approach to a problem.

The relation of optimal plans in planning studies to optimal plans in operation studies was discussed by several participants. A comment was made that optimum has completely different implications to these two points of view. The planner develops his optimum design and arrives at one decision whereas the operator must deal with conditions that change with time and, hence, should make a new study each time the change in conditions is great enough to warrant a new operational policy. An additional point raised in the discussion was that the operational optimum plan may be limited by the planner's optimum plan, since the operator must optimize the system as designed by the planner. Mr. Beard pointed out that other differences between the two were that more detail can be incorporated into an operation study, since there is more information available, and that newer technology can be applied.

The discussion of the "seat-of-the-pants" approach to optimizing a reservoir system indicated that much can be learned from this type of approach. The general opinion expressed in the seminar was that it would be necessary to systematize this technique, particularly for use when all of the "seat-of-the-pants" operators have retired.

The future direction to be taken in optimization studies was touched upon by Mr. Rockwood. He foresaw a change in the time basis of optimization studies, the tendency being to go to daily operation studies.

Mr. Beard concluded the discussion with a thought on the value of optimization studies. He thought that the extreme complexity of reservoir systems precluded a strictly mathematical approach to the problem of optimizing at this time. However, the inability to arrive at an optimum policy with this approach should not discourage anyone to the extent that they give up in their attempts to reach this policy. Rather, the search for applicable optimum policies and plans should be viewed as a building process in which a framework is being constructed for future developments.

FLEXIBILITY IN WATER RESOURCE MANAGEMENT AS RELATED TO RESERVOIRS

By

David H. Halsey[1]

INTRODUCTION

The intent of this paper is to demonstrate the necessity for generalized regulation guides as a mandatory requirement for effective, efficient and safe management of a complicated reservoir system.

To manage a water resource system efficiently, the manager is duty-bound, by professional ethics, to make the best estimate of current and future situations and react in the best interest of all concerned. This becomes extremely important with systems having multiple purposes that are readily influenced by seasons, meteorology, politics, multiple agency coordination, etc.

The Kentucky-Barkley Reservoir complex will be used as a vehicle to demonstrate the flexibility required in an actual day-to-day regulation of a flood event.

AUTHORITY

Authority for the regulation, by the Department of the Army, of flows from the Tennessee River during flood periods is contained in section 7 of the Flood Control Act of December 1944, which reads in part as follows: "This section shall not apply to the Tennessee Valley Authority except that in cases of danger from floods on the lower Ohio and Mississippi Rivers the Tennessee Valley Authority is directed to regulate the release of waters from the Tennessee River into the Ohio River in accordance with such instructions as may be issued by the War Department."

The Secretary of War, on 30 April 1947, formally designated the Division Engineer, Ohio River Division, as the responsible War Department representative.

PERTINENT DATA

A brief description of the pertinent physical characteristics of the Kentucky-Barkley complex is contained in table 1. In addition to these data, each dam contains a navigation lock that is capable of operation to

[1]Chief, Reservoir Regulation Section, Ohio River Division

TABLE 1

PERTINENT DATA

	BARKLEY	KENTUCKY
Drainage Area, Square Miles	17,600	40,200
Uncontrolled Area above Dams	7,800	18,800
Reservoir Length, Miles	118	183
Storage Capacity (flat-pool basis)		
Power, Acre-Feet (inches)	259,000(.62)*	721,000(.72)*
Flood Control, A.F. (in.)	1,472,000(3.5)*	4,010,800(4.00)*
Conservation, A.F. (in.)	610,000(1.46)*	1,991,800(1.99)*
Spillway: Capacity (Elev 375), cfs	570,000	1,050,000
Gates: Type	Tainter	Fixed-roller lift
		24 in 3
Number	12	sections each
Size, width and height, Feet	55 x 50	40 x 50
Power Features: Units	4	5
Discharge, cfs		
Full gate, 42.5 foot head	56,000	
Full gate, 48.0 foot head		52,500

*Inches of runoff based on uncontrolled area.

elevation 375, the maximum flood control pool. The projects are connected by an uncontrolled canal which is used for navigation and to divert water for power use.

OPERATING OBJECTIVES

The primary objectives of flood control regulation by Barkley and Kentucky Reservoirs are to:

1. Safeguard the Mississippi River levee system.

2. Reduce the frequency of using the Birds Point-New Madrid floodway.

3. Reduce the frequency and magnitude of flooding land outside levees along the lower Ohio and Mississippi Rivers.

The primary control point for operation of Kentucky and Barkley Reservoirs is Cairo, Illinois. The magnitude of flooding on the lower Ohio and Mississippi Rivers is related to the Cairo gage as shown in figure B, plate 1. It is obvious from figure B that the primary control factor is protecting agriculture interests.

During the occurrence of a flood, the Tennessee and Cumberland Rivers' flood discharges normally precede the flood discharges from the Ohio and Mississippi Rivers. This is a result of geographical location, in addition to the loss of valley storage on both tributaries because of the high degree of control (long reservoirs). Therefore, the reservoir discharges are normally made just prior to and following the Cairo flood crest. Figure A, plate 1, is a graphical representation of an ideal flood operation for Cairo.

As shown by figure A, plate 1, and in order to release flood waters from the system in advance of a flood, the crest stage should be predicted several days in advance. This stage is referred to as the "target" stage. During the course of a flood, additional rainfall and/or a more accurate forecast may cause the target stage to be revised. Also, the target stage will be determined by the reservoir releases necessary to limit storage utilization in proportion to the severity of the flood as indicated by the anticipated Cairo crest and the time of year. Normally, during minor and intermediate floods, the anticipated crest will include turbine capacity discharges from both projects.

Another operating objective is to draw down the reservoirs in advance of a flood. The extent of drawdown will be limited by headwater navigation depths, the natural peak flow for the system and the preserving of the total volume under the water surface profile to not less than flat pool volume for both reservoirs at the current guide curve elevation.

The full capacity of both reservoirs will be used if this will avert operation of the Birds Point-New Madrid floodway.

Plate 2 presents the normal operating guide elevations for the projects.

RESTRAINTS ON FLOOD CONTROL OPERATION

Since this discussion is centered around flood control operation, it should be pointed out, however, that this reservoir system is not single-purpose. The relative importance of other reservoir functions, in terms of optimum regulation, must also be considered. For this discussion, these purposes and physical limitations will be considered as restraints on flood control operation.

Some conditions imposing restraints to flood control operation within the Kentucky Reservoir area are:

1. Flowage rights vary considerably from 1 June to 30 November.

2. Interior drainage areas, which are separated from the reservoir area by low-level dikes, are pumped dry every spring. This is done for mosquito control and to raise food for wildlife.

3. The operation of the 3-leaf, vertical lift spillway gates at Kentucky Dam requires a special crew of men.

Since Barkley Dam was designed and built about 20 years after Kentucky Dam, the design criteria included data from model test (Mississippi Basin Model) and from prototype test (Kentucky). Therefore, the physical restraints at Barkley Dam are negligible.

The canal diverts flood waters from one reservoir to the other during the course of a flood. One foot of difference between the two reservoirs has been set as the feasible upper limit for safe navigation. Therefore, if a large inbalance of inflow to the two pools should exist, then the canal restrictions could have an effect on flood control operations.

The hydropower function could be a restraint to flood control operation in several ways. Since the Kentucky-Barkley hydropower plants are an intergral part of the TVA system, full generation and/or full peaking capacity is desired at all times. Therefore, when a flood occurs that requires partial or complete shutdown of releases from the reservoir at a time when power demands are high, a conflict could occur.

COOPERATING AGENCIES

Present arrangements provide for the exchange of hydraulic and hydrologic data among the following offices during flood periods:

Tennessee Valley Authority
River Control Branch, Knoxville, Tennessee

Weather Bureau
River Forecast Center, Kansas City, Missouri
River District Office, Cairo, Illinois

Corps of Engineers
Mississippi River Commission, Vicksburg, Mississippi
Ohio River Division, Cincinnati, Ohio
Louisville District, Louisville, Kentucky
Nashville District, Nashville, Tennessee
St. Louis District, St. Louis, Missouri
Memphis District, Memphis, Tennessee

The Ohio River Division has the responsibility of issuing the notice to begin or terminate the exchange of data, based on criteria previously agreed upon by the coordinating agencies.

DATA FLOW TO ORD

Plate 3 contains a schematic of the data flow considered necessary for operating the Kentucky-Barkley system. It is obvious that time is of the essence in the sequential flow of data, since a current analysis of the Kentucky-Barkley-Cairo complex depends on the orderly arrival of data, both observed and forecast, from many sources. Because of the time required to gather, analyze, and transmit data and because of the closed-loop-data flow around Cairo, it is essential that a cursory analysis be made as soon as observed data are available. A more detailed analysis is made as soon as the respective offices transmit their detailed predictions to ORD. Each analysis that ORD makes is based on several assumptions which vary the controllable variables within the system and change the timing sequence of the uncontrollable events.

FLOOD EXAMPLE

The following example is presented not for the purpose of evaluating the operation decisions made during the event, but to demonstrate the necessity for having general regulation plans that cover many possibilities and are flexible enough to allow the proper courses of action dictated

by a current evaluation of the situation. The following general comments pertain to the daily operation of an actual flood event that occurred during the latter part of May and first half of June. These comments are in log form.

D-DAY - Heavy rains indicate that flood stage will be reached at Cairo (below mouth of Ohio River), therefore, exchange of data is initiated. Situation: It appears that the Cumberland River portion of the total Tennessee-Cumberland runoff is greater than normal. Kentucky and Barkley discharge at turbine capacity. A Cairo flood this late in season would likely result in substantial downstream damages. Decisions: It was decided to draw down both reservoirs in advance of the flood using turbine capacity at both plants plus the amount of spillway flow at Barkley that would not raise the tailwater higher than that anticipated from Ohio River backwater.

D+1 - Cairo stage is 37.5 After an initial analysis of data, the target stage at Cairo was set at 44 to 45 feet on D+7. The decision was made to increase Barkley spill and begin spillway discharge at Kentucky. Situation: It would be desirable to increase reservoir drawdown, however, this would cause excessive canal flows. In view of anticipated major flooding at Cairo if no restrictions are placed on hydropower generation, LMVD was requested to evaluate benefits for stage-reduction increments and TVA was requested to estimate losses for increments of power reduction. Both estimates were received.

D+2 - Cairo stage is 40.1. Slight discharge reduction was made at Barkley because of tailwater control. The Mississippi River at Thebes (above the mouth of Ohio River) appears to be cresting.

D+3 - Cairo stage is 41.5. Slight additional cut at Barkley for tailwater control and decreasing Kentucky to turbine capacity at noon. Situation: Schedule daily cutbacks on both projects for next four days to zero at midnight on D+7 and regulate to control crest to approximately 44 feet on D+10 or D+11. Anticipate three to four days of zero flow. De-watered areas in Kentucky Reservoir will be flooded.

D+4 - Cairo stage is 42.2. Cutbacks continuing. Weather activity increases in the Missouri River Basin, and is anticipated in the upper Mississippi Basin, causing some apprehension.

D+5 - Cairo stage is 42.7. Cutbacks continuing. Weather immediately west of the Ohio River Basin is still cause for concern.

D+6 - Cairo stage is 43.2 Situation: Heavy showers occur over lower Ohio River and Mississippi River above Cairo. Uncontrolled local runoff could raise Cairo crest. Decision: Since runoff from shower-type storm is extremely uncertain, consideration is being given to possible earlier cut to zero. Decision will be made on D+7.

D+7 - Cairo stage is 43.6. Situation: Previous estimates of runoff from thunderstorms appear to be too high. Elevations of the two reservoir headwaters are within .40 foot. Target stage at Cairo is now 44 feet on D+9 or D+10. Decision: Cut release at both projects to zero at noon today. (Normally Barkley cutoff would be sooner because of travel time, but this would cause too much increase in the canal flow from Barkley to Kentucky reservoir.)

D+8 - Cairo stage is 43.7. Situation: Cairo stage has been steady for 23 hours; however, anticipate .1-.2 foot additional rise. Scheduled starting Barkley releases on D+11 and Kentucky releases on D+12. (Schedule consists of incremented increases for three days).

D+9 - Cairo stage is 43.8. Situation: A pollution problem (due to the lack of flow) is reported at the industrial complex below Kentucky Dam on Tennessee River. After coordination with applicable agencies, no change was made in scheduled operations.

D+10 - Cairo stage is 43.9. Situation: Possible power emergency could occur during afternoon peak load. The load in the Kentucky-Barkley area is being supplied by relatively long lines that are approaching an overload situation, therefore, the afternoon power demands could cause a relay to trip and separate the system, thus causing a blackout in a substantial area. Alternatives: (1) Put Barkley and Kentucky on an emergency standby which would allow immediate full load until connections could be made through an interconnecting link with a neighboring system. This would require from 1/2- to two hours. (This would increase downstream flooding since Cairo is at a crest.) (2) Bring one unit on line during early afternoon, instead of midnight as scheduled. This would not solve power problem but would lessen probability of load separation. Decision: After refining prediction and coordinating with appropriate agencies, ORD decided that one unit could be brought up to no-load speed by 2PM, could be on-call from 2PM until 3PM and would go on line at 3PM, without compromise of flood control responsibility. (Barkley was used because of the larger units and because of the longer travel time to Cairo.) The power system remained relatively stable throughout evening.

D+11 - Cairo stage is 43.9. Situation: Barkley is running one turbine and Kentucky discharge is zero. Power system came through without incident. Decision: Increase Barkley discharge in steps and delay Kentucky opening by three hours in order to avoid rise on Ohio River.

D+12 - Cairo stage is 43.7 and falling.

Note: Continued scheduled outflows from both projects (through turbines and spillway). Data exchange was terminated on D+16.

Flood Summary: During the early stages of the flood, downstream farmers were requesting, through Congressman, the Kentucky and Barkley be cut off sooner. However, they were ultimately convinced (?) that the Cairo crest would have been the same.

A complication that could have affected the operation concerned the flood easements in Kentucky Reservoir. The easement elevation is substantially reduced on 1 June and the above described flood caused the pool elevation to crest just below the easement taking line.

SUMMARY

The fixed-rule criteria evolved during a period of building individual projects for one dominant purpose (generally flood control). The single projects have grown into systems of multipurpose projects that require almost daily evaluations of authorized purposes based on the continuous detailed analysis of large quantities of data. Attitudes and emphasis have changed with time, in that the affected entities have become more aware of their interest, demanding more sophisticated answers to an increasing number of questions pertaining to the management of reservoirs. These questions cannot be intelligently answered using firm rule curves for every event and disregarding immediate circumstances.

The electronic computer has made it possible for a reservoir system manager to analyze large volumes of data in a very short period. The manager must have the latitude to react based on the "best" solution at the time.

NEEDS FOR FUTURE DEVELOPMENT OF TECHNIQUES

Techniques should be developed so damages and/or benefits can be quickly and accurately evaluated on a compatible basis. For example, if the probability of a power blackout is so much, what benefit would accrue if it were averted? How can you compare tangible and intangible benefits equitably? Should dollars be the sole unit of comparison?

An Engineering Manual on Water Resource Management other than the present engineering manual on Reservoir Regulation that would incorporate the thought processes that should be used in evaluating a system, that would reflect the present state-of-the-art, should be published. The manual should avoid detailed hydrology and hydraulics, but should include techniques, concepts and principles, and be usable with computers and permit flexible and comprehensive regulation rules. The thought portrayed by EM 1110-2-3600, which uses fixed rules for a one-reservoir system and states that each purpose could be operated using separate regulation schedules, should be replaced by a more flexible and functional document.

SUMMARY OF DISCUSSION

Compiled by E. F. Hawkins[1]

There was considerable discussion of the definition of a rule curve, as used in this paper. One suggestion was that a rule curve is a fixed storage-time relation governing the operation of (releases, power generation) a reservoir. A guide curve would then be a flexible guideline, which could be varied based on the engineer's judgment of the situation. It was pointed out that there is often a communications problem between engineers due to the various definitions of a rule curve, and that it might be desirable to add a modifier to clarify the meaning in each case.

The question of possible adverse effects of drawing down a reservoir in advance of a flood was discussed. During this portion of the flood operation, the attempt is to constrain releases to the maximum that would later have occurred naturally, based on the forecasts of streamflows. However, the fact that there is then less warning for those who must remove cattle, equipment, etc., from the flood plain must be taken into consideration.

There was a discussion of possible adverse effects of prolonging moderate flows beyond the time that they would have ceased naturally. This is definitely a serious consideration, since regulation can delay the planting or replanting of crops. There is often a fine balance between the extent and duration of flooding. It was pointed out that the effects of combining releases with tributary flows further downstream are difficult to forecast and that the best release pattern for control at remote downstream points would depend largely on probabilistic factors.

There was a suggestion that a "management manual" would be more appropriate than a "regulation manual". However, it was pointed out that regulations based on extensive study of all factors should not be over-ridden easily by immediate problems of minority interests, and that this is the tendency where large latitude of operation exists.

[1]Hydraulic Engineer, Training and Methods Branch, The Hydrologic Engineering Center

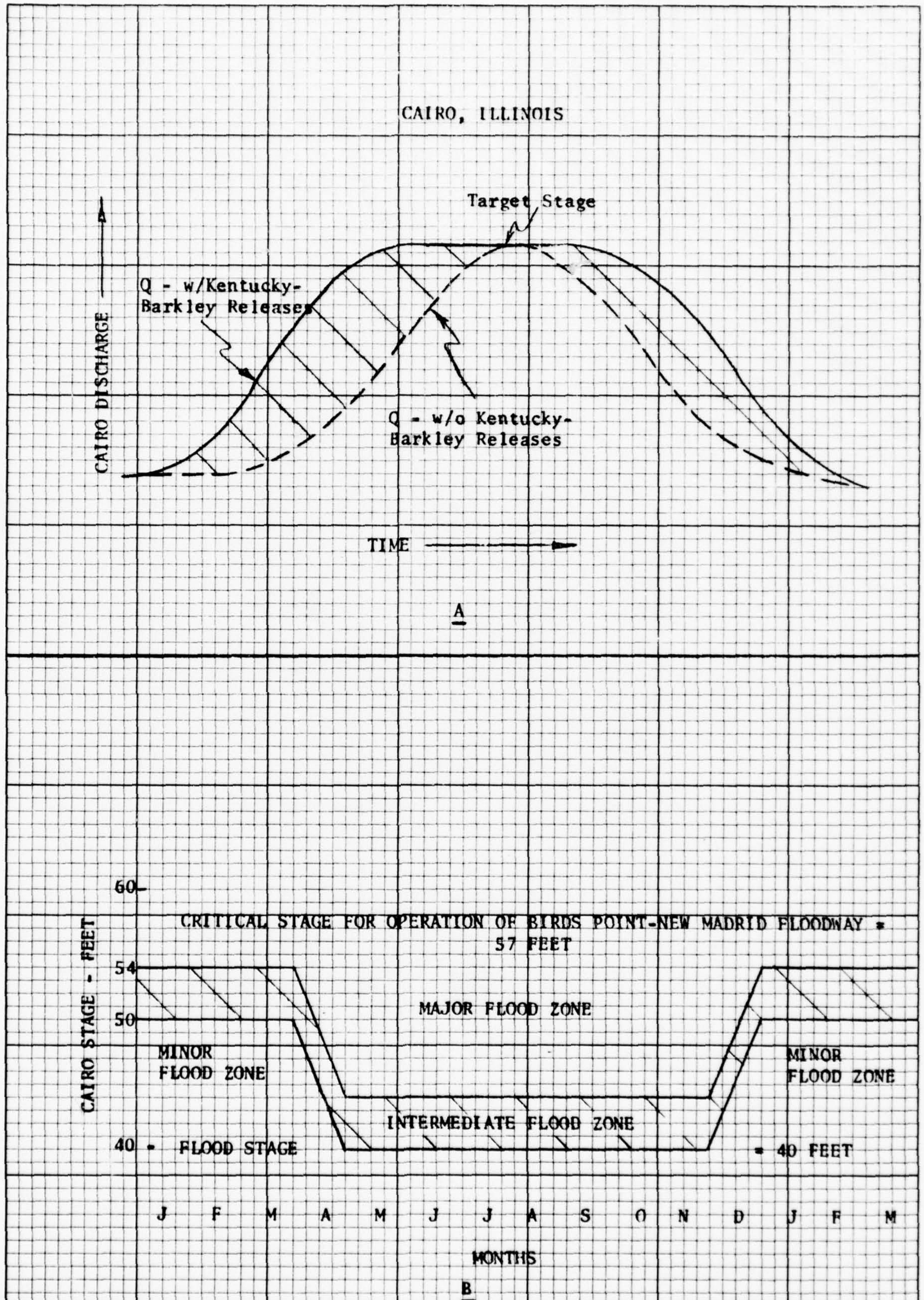
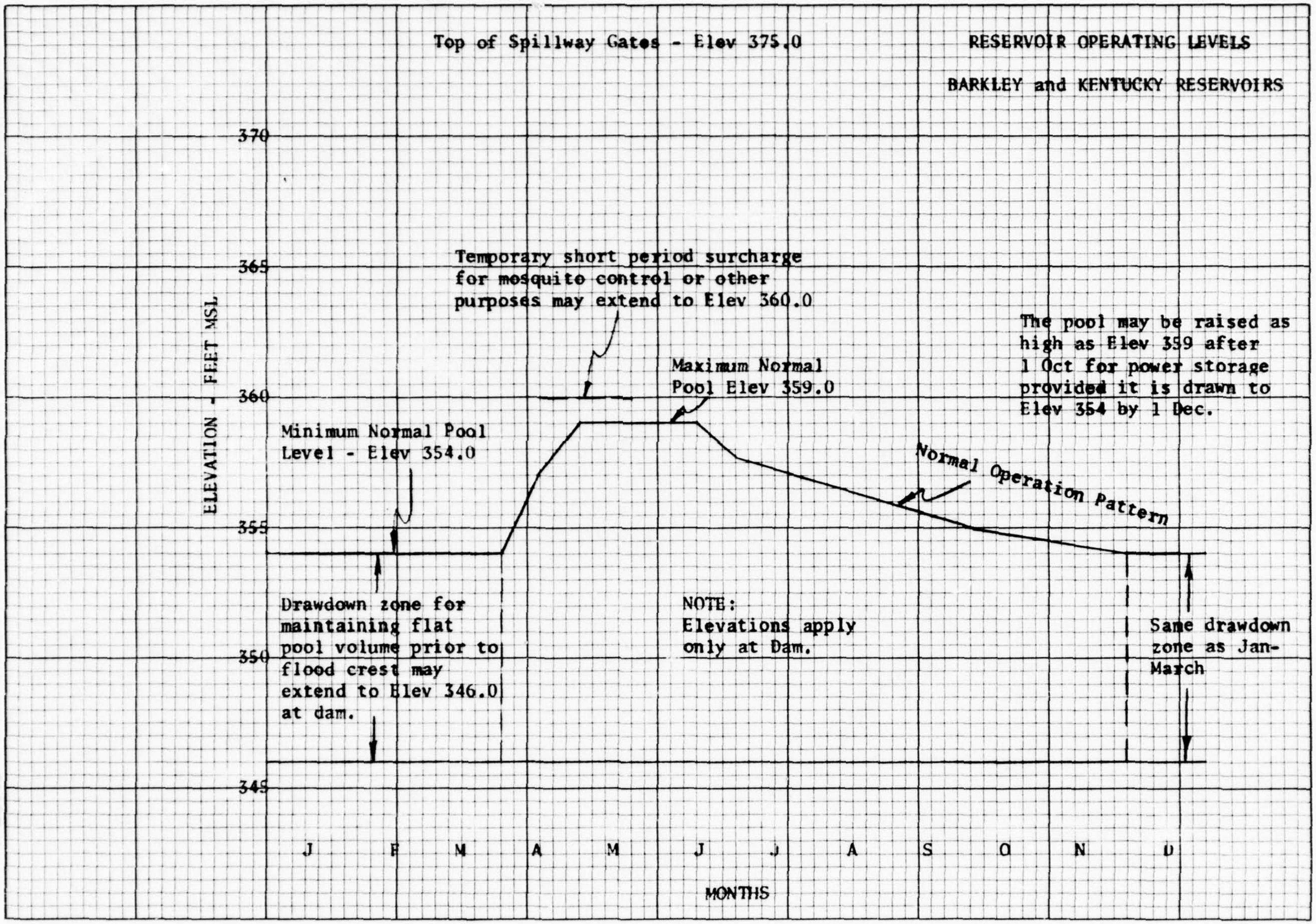

CAIRO, ILLINOIS
Target Stage
Q - w/Kentucky-Barkley Releases
Q - w/o Kentucky-Barkley Releases
CAIRO DISCHARGE
TIME
A
60
54
50
40
CRITICAL STAGE FOR OPERATION OF BIRDS POINT-NEW MADRID FLOODWAY = 57 FEET
MAJOR FLOOD ZONE
MINOR FLOOD ZONE
MINOR FLOOD ZONE
INTERMEDIATE FLOOD ZONE
FLOOD STAGE
= 40 FEET
CAIRO STAGE - FEET
J F M A M J J A S O N D J F M
MONTHS
B

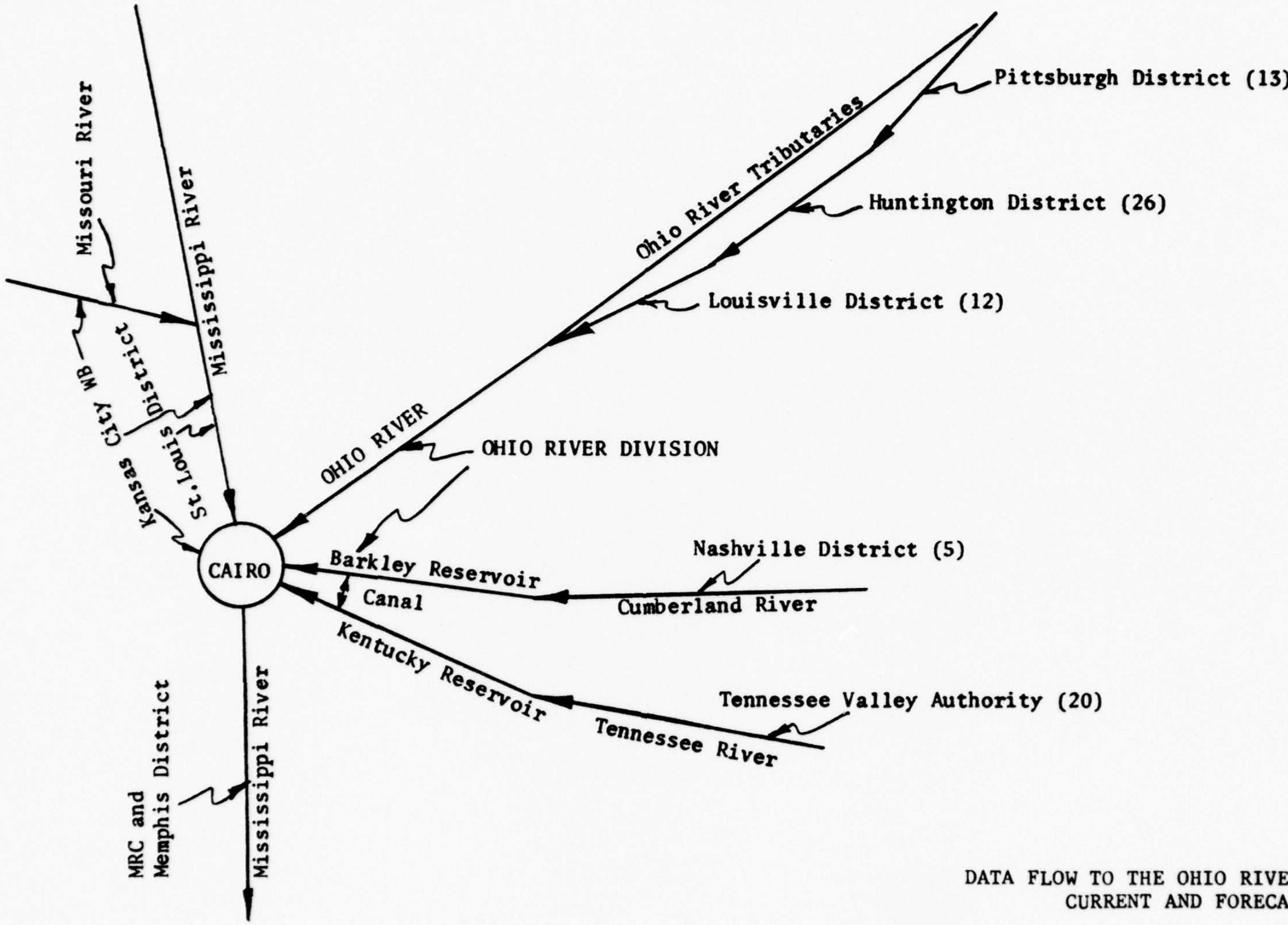
PLATE 1



RESERVOIR OPERATING LEVELS
BARKLEY and KENTUCKY RESERVOIRS
Top of Spillway Gates - Elev 375.0
Temporary short period surcharge for mosquito control or other purposes may extend to Elev 360.0
Maximum Normal Pool Elev 359.0
The pool may be raised as high as Elev 359 after 1 Oct for power storage provided it is drawn to Elev 354 by 1 Dec.
Minimum Normal Pool Level - Elev 354.0
Normal Operation Pattern
Drawdown zone for maintaining flat pool volume prior to flood crest may extend to Elev 346.0 at dam.
NOTE: Elevations apply only at Dam.
Same drawdown zone as Jan-March
ELEVATION - FEET MSL
370
365
360
355
350
345
J F M A M J J A S O N D
MONTHS

NOTE: (76) - No. of existing flood control reservoirs.

Total = (56) ORD
(20) TVA



DATA FLOW TO THE OHIO RIVER DIVISION
CURRENT AND FORECAST

PLATE 3

13

FLOOD REGULATION OF KANSAS RIVER
BASIN RESERVOIRS

by

R. Terry Coomes[1]

The specifics of this paper are confined to reservoir regulation for flood control within the 60,060 square miles drained by the Kansas River; however, the regulation principles have wide application. This basin, with a population in excess of one million, contains two cities with more than 100,000 people and the river is of vital concern to the area of metropolitan Kansas City, where another million people live and work. Figure 1 shows the principal watersheds in the basin, their size in square miles, and mean annual flow in cubic feet per second. The flow is highly variable and is primarily runoff from rainfall, with only a minor amount of snowmelt. The Kansas River basin comprises 11 percent of the area and contributes eight percent of the flow of the Missouri River basin. The Kansas River flow is regulated by 17 projects. Figure 2 shows the location of these projects and the agency which built and operates each. Tuttle Creek and Perry, in the lower Kansas River basin, are nearest to the major damage centers at Topeka and Kansas City. Regulation of the Republican and its tributaries is accomplished by Milford, Lovewell, Harlan County, Norton, Harry Strunk, Hugh Butler, Enders, Swanson, and Bonny Reservoirs. On the Smoky Hill tributaries, Kirwin, Webster, and Glen Elder control the Solomon and Wilson the Saline, while Cedar Bluff and Kanopolis serve the main stem.

Figure 3 is a bargraph showing the storage zones in the reservoirs just discussed in units of 1,000,000 acre-feet.

Total storage in the basin amounts to 2.7 million acre-feet of inactive and conservation storage and 6.5 million acre-feet of flood control storage. The six most downstream projects contain 75 percent of the gross flood control capacity. All flood control storage space in the projects is allocated exclusively for use in the reduction of flood damages, with no seasonal, dual-use zones.

The regulation of these 17 projects for flood control is the responsibility of the Kansas City District of the Corps of Engineers. The number of projects involved and the complexity of the basin have made it necessary to develop a scheme of regulation which interrelates the projects. This regulation

[1] Chief, Water Control Section, Kansas City District

scheme is designed to accomplish three main objectives which, in their order of priority, are (1) protect the damage centers, (2) evacuate the system flood storage, and (3) place evacuation priority in reservoirs in the system which are most likely to lose their ability to protect the damage centers. As far as criteria are concerned the first two of these are really inseparable, that is, the target protection levels at the damage centers, along with the uncontrolled flows, define the evacuation rate. The third criterion is subordinate to the first two. The regulation of any gated flood control project requires the adoption of flood protection levels, or targets, for various reaches downstream from the project. In many cases this is the most significant engineering decision to be made regarding the flood operations of the project. In the Kansas River basin each reach typically has several characteristic damage levels defined by farming practices, roads, residential and business buildings, and leveed high damage areas. Farming practices include the cultivation of sloughs, low shelves, and fertile flood plains. County roads and bridges are frequently on a level with the low shelf. Without exception, residential and business developments are considered part of the high level flood plain. The current policy in the Kansas City District is to attempt complete protection of the high level flood plain and its associated urban developments, partial protection of the agricultural areas on the low shelf, and no protection of the sloughs or other extremely marginal developments. This is illustrated on figure 4. For simplicity, the highest level of protection (residential, commercial, and high level agriculture) is designated as Phase III and the lower level of protection is Phase II. Stages and discharges corresponding to these two levels have been carefully determined, by field reconnaissance, for each reach in the basin. Phase I defines a lower target level with a safety factor for subsequent runoff or forecasting errors. The three target levels are illustrated on a typical stage damage curve shown on figure 4. Phase II corresponds to very minor damage and Phase III to the break point on the damage curve.

The common floods up to about a five-year recurrence interval are regulated in the Phase I category. Maximum damage reduction is achieved and a 40 percent margin for error is allowed. Events in the 5 to 50-year range are regulated in the Phase II category, and maximum damage reduction is attempted without a safety factor. The more extreme events are regulated with Phase III targets. At the Phase III level, protection of the low-level agriculture is abandoned in favor of preserving storage to give increased assurance of protection of the high damage areas and towns, such as Topeka and Kansas City, which are endangered only by extreme floods. This corresponds essentially to the criteria outlined as regulation method C in EM 1110-2-3600.

The protection levels are tied to reservoir levels. The basic assumption is that the more water impounded in the reservoir, the less capability remains in the project to protect the damage centers from additional storms. Zones

have been established in each reservoir called Phase I, II, and III which correspond to the downstream protection levels. The derivation of the dividing lines between the reservoir storage zones warrants considerable attention and is second in importance only to the selection of the protection levels. The lines are varied seasonally and are unique to a particular project. They are called seasonal guidelines and are derived by a combination of analytical analyses and engineering judgment.

The division between Phase II and Phase III signifies the point at which we are willing to knowingly allow damage to the low-level agricultural developments in order to maintain some flood control capability in the project. A Phase III release is felt to be economically and hydrologically justified as described above, but politically difficult and is reserved for extreme events. The dividing line between Phase II and III has been set for all projects at 90 percent of the flood control capacity during the nonflood season and 80 percent during the flood season.

The division between Phase I and Phase II signifies the level at which the project is regulated for maximum damage reduction without a margin for error. If the forecast of uncontrolled downstream inflow is on the low side or if it rains unexpectedly, damage will result. This division is expected to be an indication of that particular reservoir's capability to provide maximum protection during any time of the year. To arrive at this division a monthly index has been developed which serves as an indicator of the project's capability for the next 90 days. The 90-day period was selected because historically, in the Kansas River basin, a series of floods over several months is required to produce runoff volumes which approach project capacity. Also, a flood series extended over several months is the most strenuous test for a regulation scheme for this system. The index is the ratio of two factors, each of which in turn has two components. It consists of project flood control capacity plus the volume of a 30-day channel capacity release, divided by the current month's 25-percent-chance inflow volume plus the 25-percent-chance inflow volume for the next two months. This essentially is a ratio of project capacity to the 90-day, 25-percent-chance inflow volume. It is assumed that, during any 90-day storm period, the reservoirs will be able to release one-third of the time at channel capacity and so this volume is considered part of the 90-day regulating capacity of the reservoir. The 25-percent-chance inflow volume was chosen because it approximates the size of flood to be regulated in Phase I and is, therefore, significant to the Phase I-II dividing line. A plot of the monthly indices for two Kansas River basin projects is shown on figure 5. Engineering judgment is required in making the transition from the graph of a dimensionless index to a seasonal guideline with percent of flood control storage as an ordinate. The only limitation observed is that the guideline dividing Phase I and II shall not go lower than 20 percent or higher than 50 percent of the flood control storage. These limits provide a degree of consistency and conservatism in

the operation of the various projects. The adopted guidelines for two of the projects are shown on figure 6.

We are now equipped to operate a single Kansas River basin project. Protection levels have been established based upon the level of development along the river. The corresponding division of the reservoir flood control pool has been made based upon the ratio of total project flood storage and evacuation capability to seasonal inflow characteristics. The regulation of the project requires that the reservoir phase be determined from the current pool elevation and the uncontrolled flow be forecasted and subtracted from the target discharge at the various control points. The least of these discharges will be the reservoir release for that time period. However, there are 17 reservoirs in the Kansas River basin, all contributing to the protection of Kansas City. The overall solution is obviously not so simple.

There are two new problems to be solved in the regulation of multiple reservoir systems: release priorities between tandem projects, and priorities between parallel projects. The Kansas River basin has numerous examples of both.

In a tandem system, the decision to be made is whether or not to release from the upstream project into the downstream project. Generally, the philosophy of flood control people is to evacuate the downstream project first as it is the last point of control, assuming, of course, that the damage center is downstream. If the reservoirs were equivalent on every basis, except that one lay upstream of the other, then the solution might be that simple. In fact, projects are rarely equivalent in any characteristic. Design criteria change over a period of time, sites dictate some characteristics, and economics dictate others. An example in the Kansas River basin is the Harlan County-Milford tandem combination.

Milford Dam was completed in 1964, has 3.7 inches of flood storage on the intervening area, and 0.6 inches overall. The spillway is uncontrolled and the surcharge pool (1,414,000 acre-feet) must be 11 percent full for the capacity of the chute to equal a Phase III release.

Harlan County Dam, 230 miles upstream from Milford, was completed in 1952, has 1.1 inches of flood storage on the intervening drainage area, and 0.45 inch on the gross drainage area. The spillway is gated and the surcharge pool (46,800 acre-feet) need only be 0.5 percent full to permit a Phase III release. Flood damages in the reach between the two projects exceeded $10,000,000 in one year preceding the construction of Harlan County Dam. The point is that neither project can be evacuated at the expense of the other. The projects releases must be coordinated so that each project retains some space for protection of its damage centers from additional runoff.

In the Kansas River basin, the seasonal guidelines are used as a basis for both tandem and parallel priorities. The guidelines are designed to be a measure of reservoir capability and should logically be used in the establishment of evacuation priorities. In tandem projects, this usually results in a slight favoritism toward evacuating the downstream project. The diagram for Harlan County-Milford was derived as shown on figure 7. The dividing line on the graph indicates whether the upstream project can release or not. The line is developed by using the corresponding minimum Phase II and Phase III elevations as break points and drawing straight lines between these points and the 0-0 percent, 100-100 percent corners. In the application of the guidelines, travel time between the projects is considered so that the pool elevations applied to the tandem balance chart are coincident. The operation of individual projects has been described as well as the overriding constraint of a tandem criterion. The remaining complication is illustrated by the parallel reservoir systems such as the Milford-Tuttle Creek-Perry combination in the lower Kansas River basin.

These three parallel reservoirs jointly contribute to the protection of several reaches, including Kansas City. At times, a single control point with a high uncontrolled flow may restrict the releases from all three projects. At such a time a scheme is necessary to divide the available channel capacity among the contributing projects. Again, the seasonal guidelines are used to establish priorities. The reservoir in the higher phase is given the first priority in making releases. Should this reservoir not be able to use all of the available channel capacity the reservoir with the next highest phase is allocated the remainder of the channel capacity. Using the seasonal guidelines as a basis for evacuation priorities gives consideration, not only to the amount of storage occupied, but to flood pool capacity, release capability, and historical inflow volumes. These are considered critical characteristics of a flood control project, excluding the surcharge operations. Through many operation studies this has proven more realistic than a proration relying only on percent of storage occupied.

There remains the problem of priorities within the storage zones. For instance, if Milford, Tuttle Creek, and Perry were all in Phase II, which would have the first evacuation priority? Regulation studies indicate that this condition will occur less than ten percent of the time that major flood events are in progress; however, regulation plans must consider rare events.

The philosophy of priorities within storage zones is that the first priority project is the one that is most likely to allow the greatest damage if the top of flood pool is exceeded. As long as the top of flood pool is not exceeded the damage centers remain protected by any and all projects. But the degree of protection offered by projects in the surcharge zone varies from almost complete protection at Wilson Reservoir to almost

no protection at Enders and Harlan County Reservoirs. Therefore, of two parallel projects in the same phase, the project that poses the greatest threat in a surcharge operation is the one given first priority in evacuation, thereby lowering the probability of encroachment into the surcharge pool. The following equation is used to define a priority weighting factor, or character, as it is called here.

$$C = \frac{VQ}{Sq}$$

Where

C = Character index
V = 25-year flood volume
S = Surcharge storage capacity
Q = Release at one-half surcharge pool
q = Phase-II release

The 25-year flood volume provides an indication of the runoff characteristics likely to force a surcharge operation. In dividing the 25-year flood volume by the surcharge capacity, a perspective is obtained on the size of the surcharge pool in relation to the runoff likely to occur. The minimum release at one-half surcharge pool divided by the channel capacity indicates the degree of damage to be caused by a surcharge operation. The reservoir character combines the factors which indicate the likelihood of a surcharge operation and the ability of the project to reduce damages, should such an event occur.

Computation of Reservoir Characters

Enders Reservoir: $\frac{(8,100)(70,000)}{(6,200)(500)} = 182$

Harlan County Reservoir: $\frac{(91,800)(100,000)}{(46,800)(4,000)} = 49$

Wilson Reservoir: $\frac{(80,100)(1,000)}{(1,220,000)(4,000)} = 0.02$

This analysis indicates that it is more critical for Enders and Harlan County to exceed their flood pool capacity than for Wilson by a factor of 182 to 0.02 and 49 to 0.02 respectively. This is a radical contrast that demonstrates the extreme differences in the design of the projects. The character is used as a weighting factor to be multiplied by the percent of flood storage occupied to compute the proration of available channel capacity among the various parallel projects in the same phase. For example, if the flood pools of Milford, Tuttle Creek, and Perry were each in Phase II and 60 percent full and the available channel capacity was 25,000 cfs, the following releases would be made:

Tuttle Creek:	(character = 4.3) x 60%	=	2.58
Milford:	(character = 3.1)x 60%	=	1.86
Perry:	(character = 0.8) x 60%	=	0.48
	Total		4.92

Tuttle Creek release = 25,000 cfs x 2.58/4.92	=	13,000 cfs
Milford release = 25,000 cfs x 1.86/4.92	=	9,500 cfs
Perry release = 25,000 cfs x 0.48/4.92	=	2,500 cfs
Total		25,000 cfs

As previously stated, the evacuation priority between parallel projects is first established by phase. The reservoir with its pool in the highest phase, as defined by the seasonal guidelines, gets the exclusive first priority. If two or more projects have the same phase, the available channel capacity is prorated on the basis of the percent of flood storage occupied as weighted by the reservoir character. This has proved to be an efficient evacuation process. The reservoir in the highest phase, by definition, provides less protection to the downstream areas than a project in a lower phase. This logically makes it important to give evacuation priority to the higher-phase project. When the projects are in the same phase and are providing the same degree of protection, then the priority goes to the project most likely to lose its ability to protect the major damage areas, namely, the project with the highest product of character times percent of flood storage occupied.

The following list summarizes the factors considered in determining parallel priorities by this scheme:

Seasonal guidelines	90 day, 25% chance inflow volume Total project flood storage capacity 30-day release capability
Reservoir Character	25% year inflow flood volume Total project surcharge storage capacity Surcharge release characteristics Channel capacity Current percent of flood pool occupied

These factors represent the characteristics of Kansas River basin reservoirs that we feel are pertinent to system regulation for flood control. This regulation scheme, as in all flood control programs, is a plan for efficient and systematic evacuation of water impounded in reservoir flood control pools. This is not a reservoir storage balancing scheme. It is a reservoir evacuation scheme. The only time the reservoirs in the system are in balance is when they are empty. The river channel at the critical control point is kept filled to the appropriate protection level at all times during the evacuation process. The reservoir priority techniques do not restrict the

evacuation of the system. The basic mechanics of the computations have not been described here. They are lengthy and tedious for a basin-wide flood and are definitely best handled through the use of a digital computer. These techniques have been incorporated into a mathematical model of the Kansas River basin. Additional details of the regulation plan can be obtained by request of the Kansas City District.

SUMMARY OF DISCUSSION

Compiled by J. F. Harsh[1]

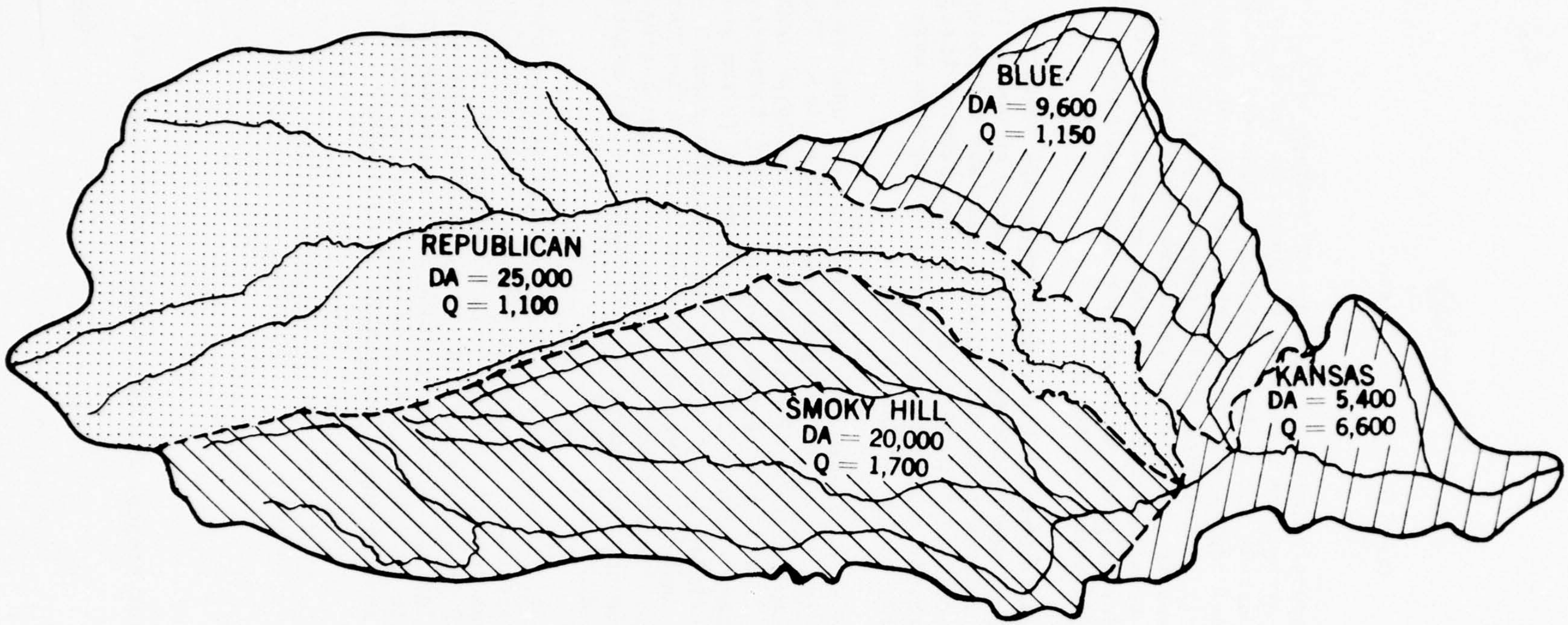
There was some discussion on how the delay and storage effects of channels in the stream system are taken into account when selecting reservoir releases throughout the system. The model considers the lag time of a flow at channel capacity between each reservoir and the major damage centers. A fairly generalized digital computer program, based on six hour periods, is used to evaluate and establish the operation plan. An analog model, which simulates the Kansas River portion of the basin, is used to examine different patterns of water release and streamflow routing techniques at different control points.

A question arose as to whether the system design and operation plan could be seriously biased by the particular nature of one or two historical floods. It is true that historical floods have been used in establishing reservoir operational criteria. However, several historical floods and several synthetic events representative of the area were used to test the applicability of the system operation.

There was a question as to what primary criteria were used to select the operation plan for the Kansas River Basin reservoir system. The primary objective of the operation plan is to protect the major damage centers, including the leveed urban areas, such as Topeka, Lawrence, and Kansas City. These damage centers were checked to see if levees and other developments were adequately protected under the operation plans. Several operational plans were tested with varying degrees of protection through a critical storm series. In addition to assuring protection during major floods, the plan was designed to assure maximum flood control capability in the system at the end of minor floods.

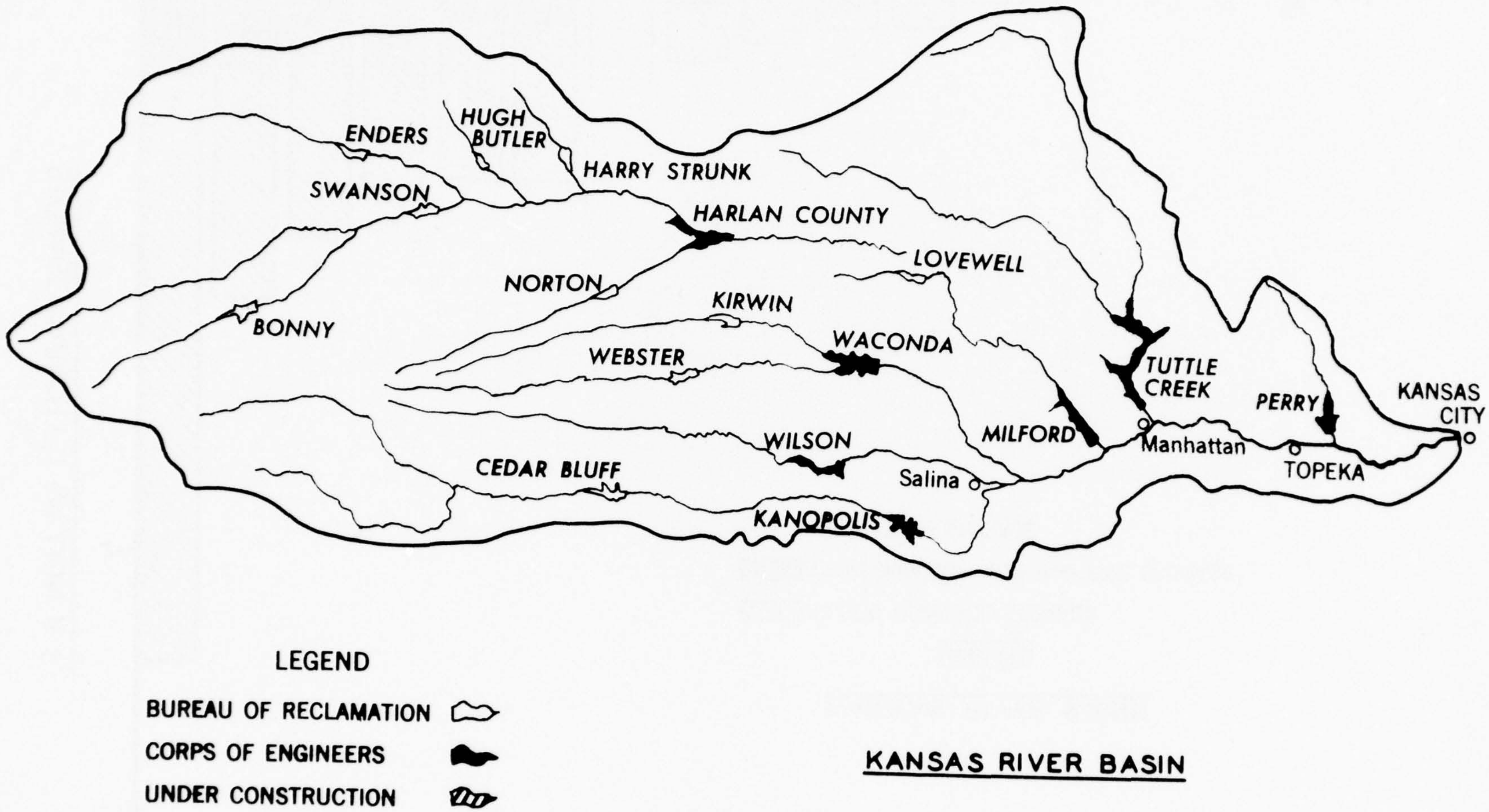
The three phases, I, II, and III, represent a step release plan of operation. Mr. Beard questioned whether such a plan could encourage the development of the areas subject to infrequent flooding. Mr. Coomes agreed that problems of this character are anticipated to occur with Phase III reservoir releases. However, a Phase III release has not yet been necessary. When it becomes necessary to use Phase III releases, the situation will be serious enough to warrant the releases.

[1]Geologist, Ground Water Branch, The Hydrologic Engineering Center



KANSAS RIVER BASIN

FIGURE 1



KANSAS RIVER BASIN

FIGURE 2

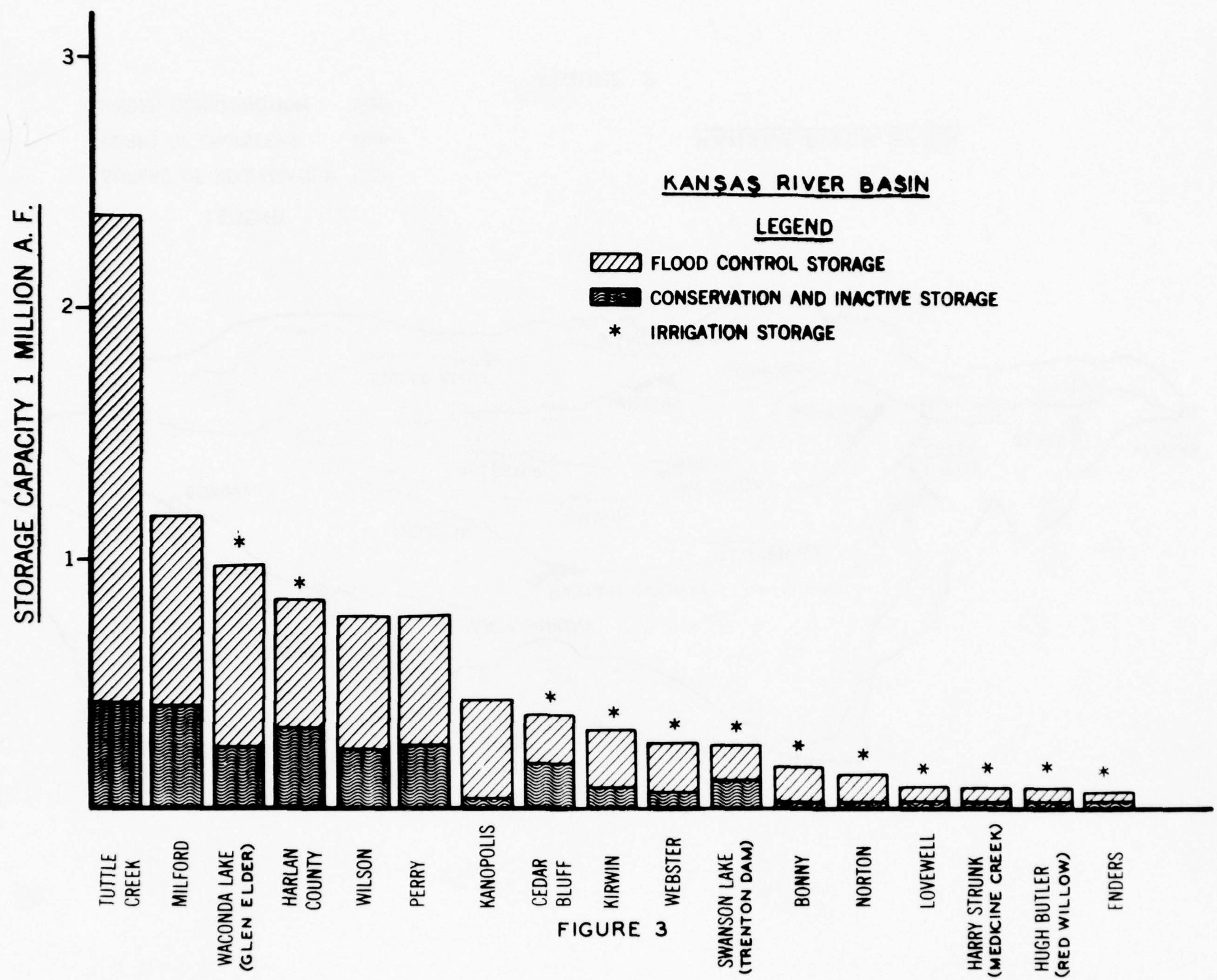
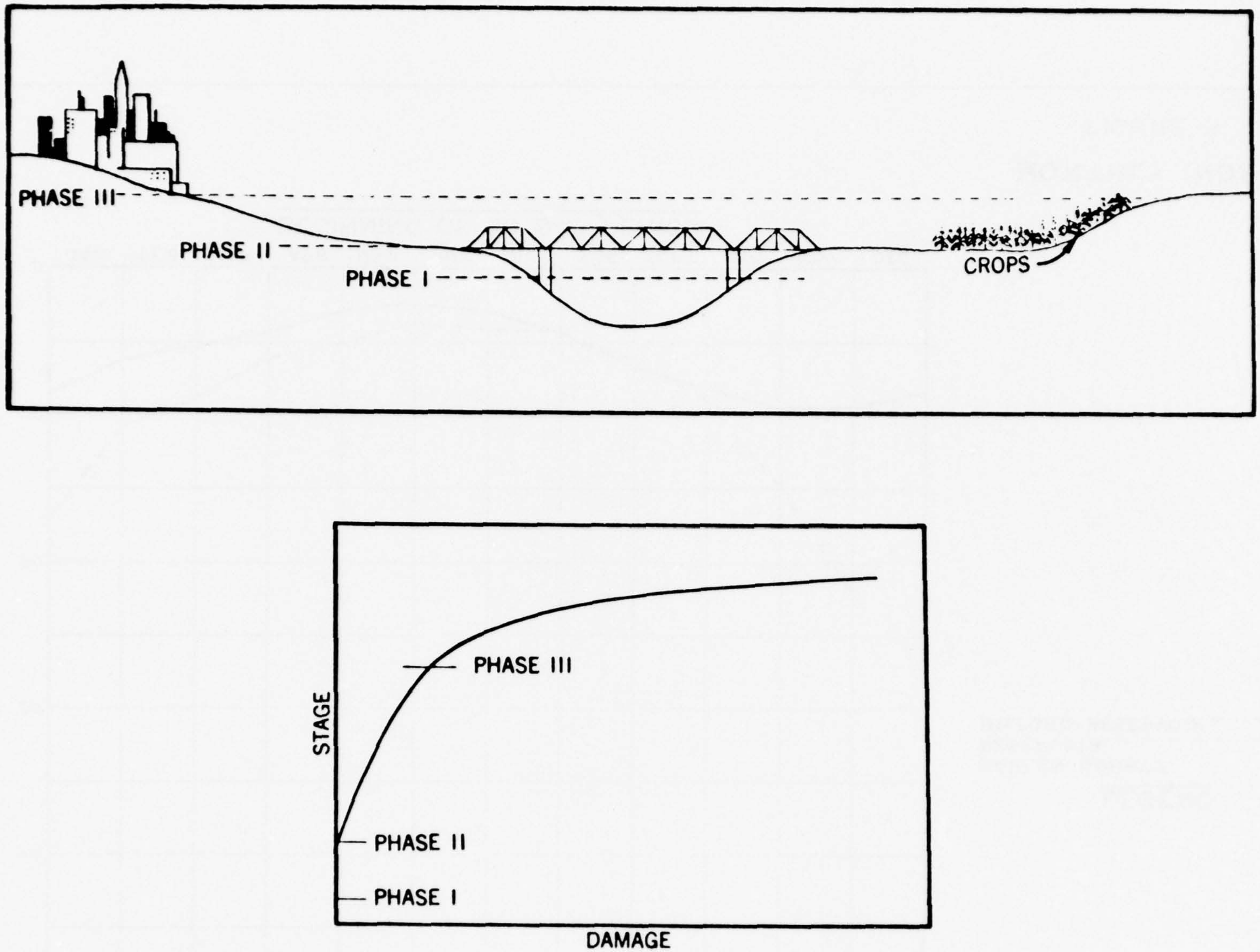
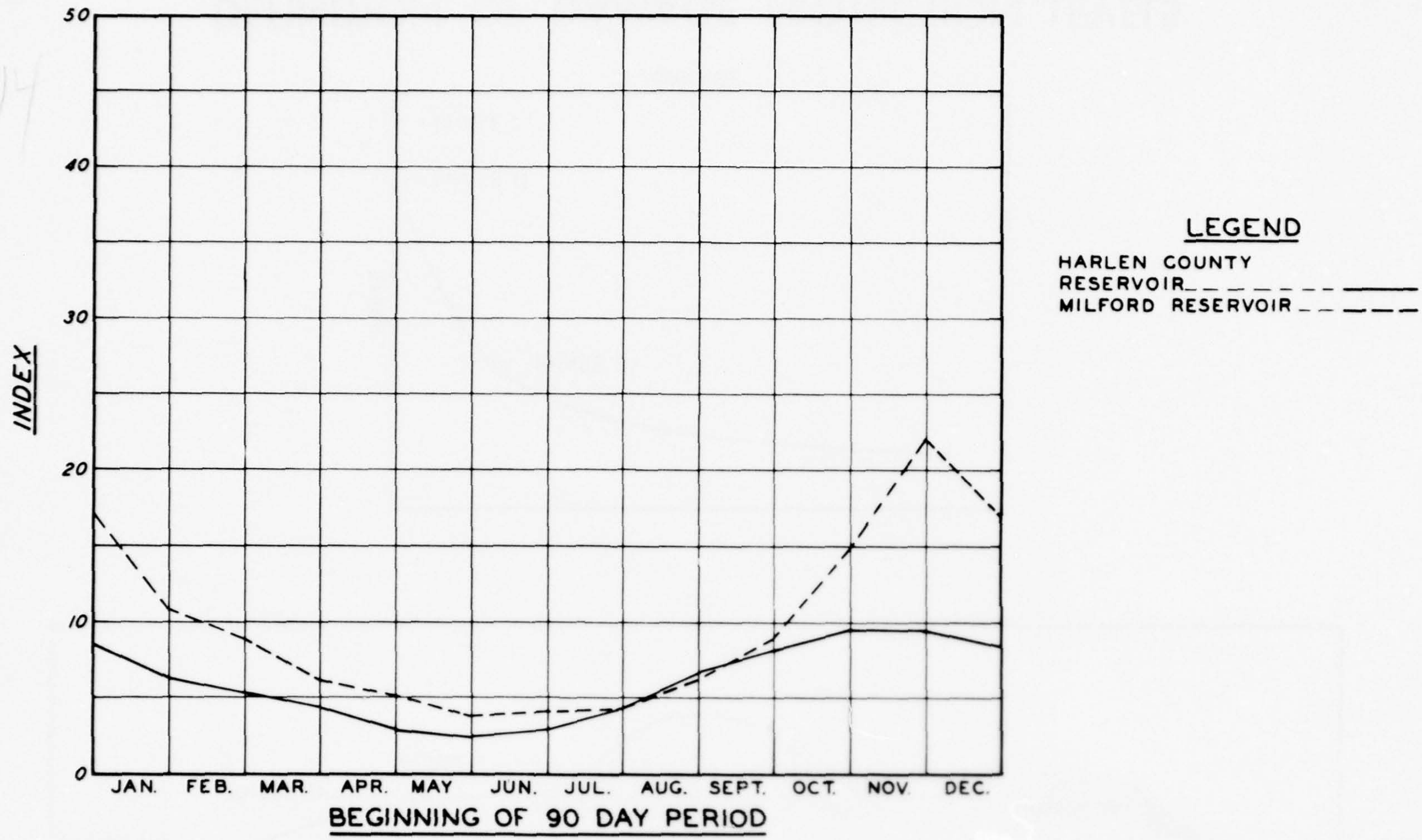

KANSAS RIVER BASIN
LEGEND
FLOOD CONTROL STORAGE
CONSERVATION AND INACTIVE STORAGE
* IRRIGATION STORAGE
STORAGE CAPACITY 1 MILLION A. F.
3
2
1
TUTTLE CREEK
MILFORD
WACONDA LAKE (GLEN ELDER)
HARLAN COUNTY
WILSON
PERRY
KANOPOLIS
CEDAR BLUFF
KIRWIN
WEBSTER
SWANSON LAKE (TRENTON DAM)
BONNY
NORTON
LOVEWELL
HARRY STRUNK (MEDICINE CREEK)
HUGH BUTLER (RED WILLOW)
ENDERS

FIGURE 3



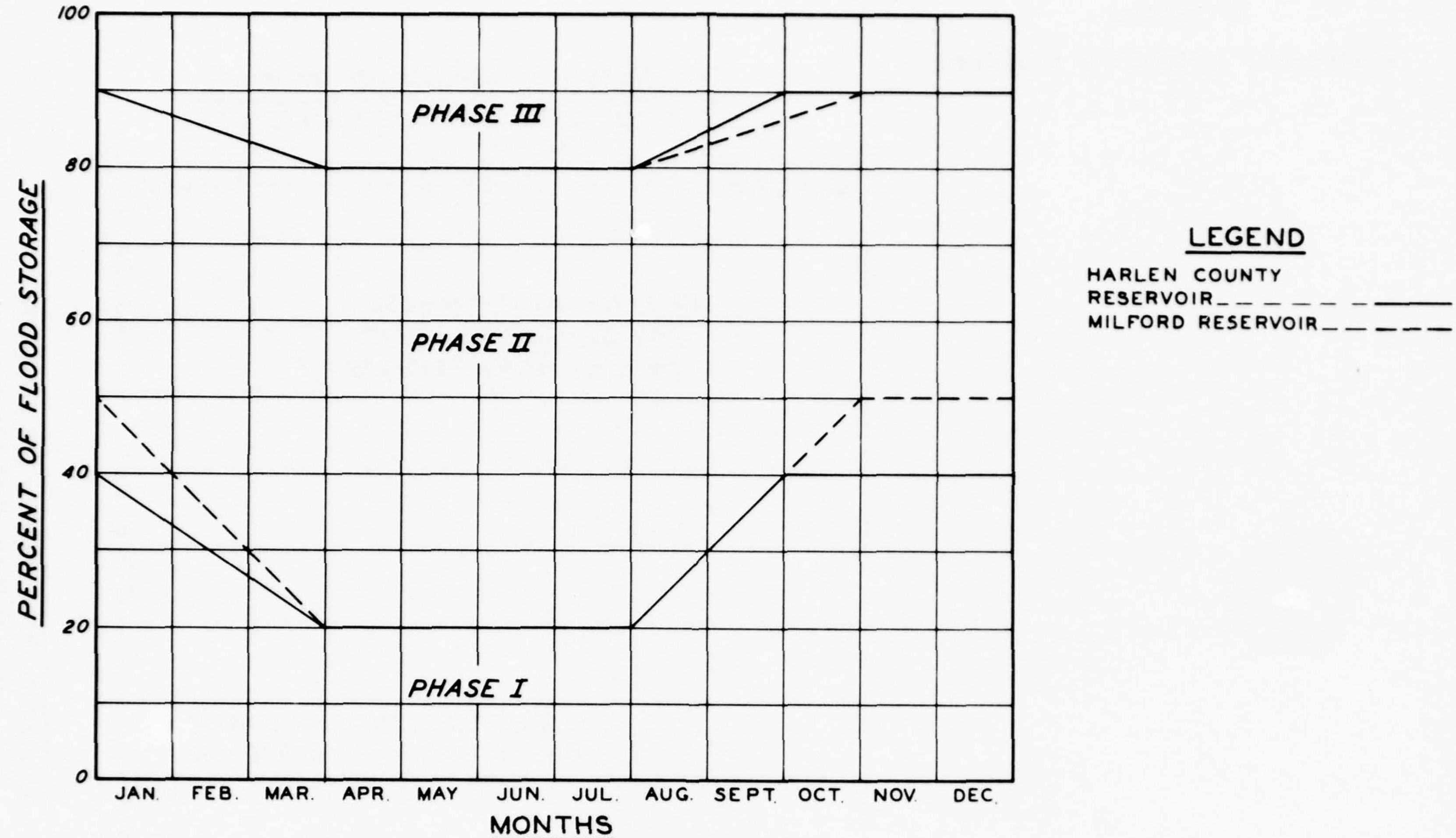
DEFINITION OF DAMAGE PROTECTION LEVELS

FIGURE 4



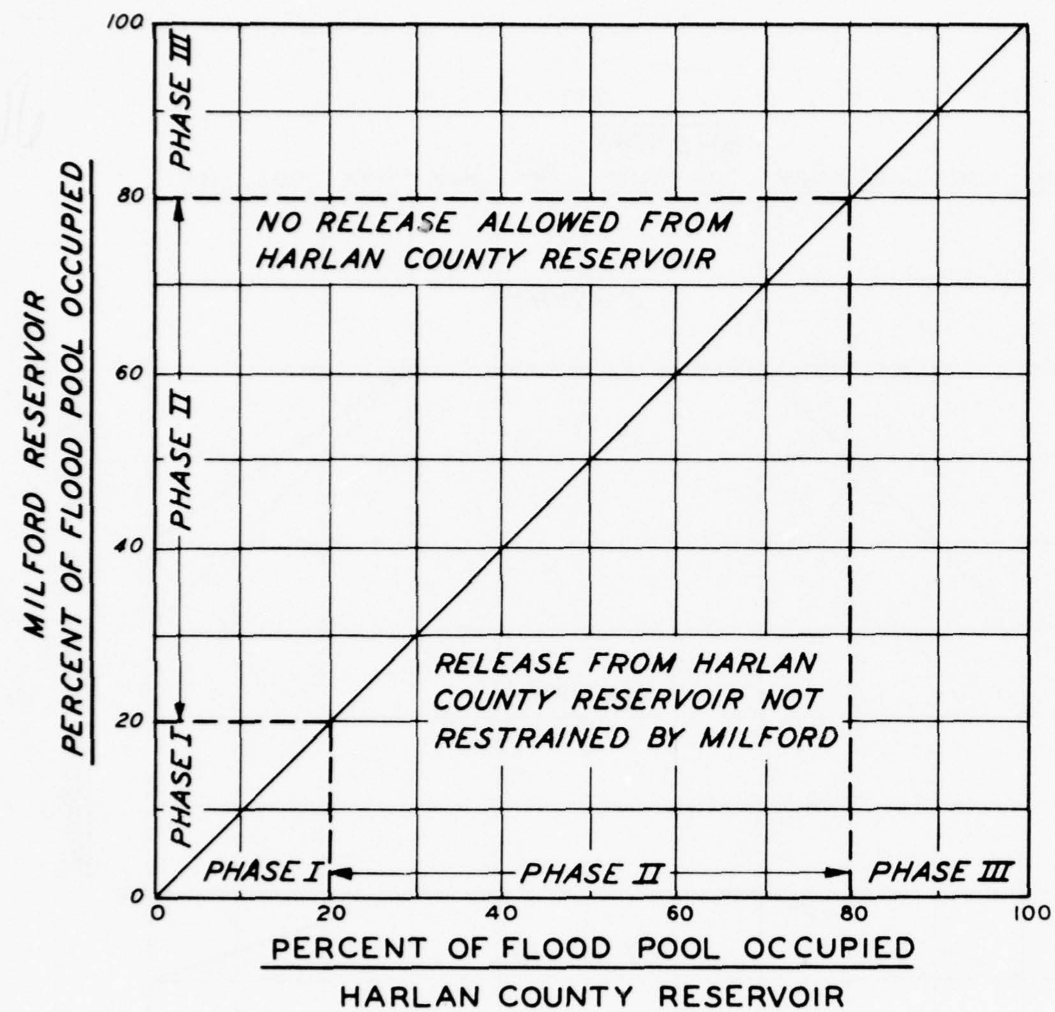
MONTHLY INDEX

FIGURE 5



SEASONAL GUIDE LINE

FIGURE 6



TANDEM BALANCE DIAGRAM

FIGURE 7

OPERATION STUDIES OF THE KASKASKIA RIVER RESERVOIR SYSTEM

by

William H. Pinner[1]

INTRODUCTION

Operation studies of the Kaskaskia River Reservoir System were planned to resolve problems of reservoir operation. A series of operation plans are required to meet operational conditions as they change in time. Presently, a single reservoir is in operation. In the near future, two reservoirs will operate as a system. Ultimately, it is anticipated that the system will include other measures in conjunction with reservoirs to resolve new problems as they develop. A description of the basin and projects of the system is followed by discussion of the problems involved in the operation studies and the study techniques currently in use and needed in the future.

DESCRIPTION OF BASIN

The Kaskaskia River Basin lies wholly in the State of Illinois and has a total drainage area of 5,840 square miles. The basin is shown on the attached map. The basin has a median length of about 175 miles, an extreme width of 55 miles, and an average width of about 33 miles. The topography of the basin is generally flat or gently rolling, except for broken terrain near the streams.

The Kaskaskia River rises in the east-central part of the state. It flows in a general southwesterly direction approximately 325 river miles and empties into the Mississippi River about 8 miles above Chester, Illinois, or approximately 118 miles above the mouth of the Ohio River. The course of the river is tortuous with many oxbow bends. Banks of the river and its tributaries are generally from 1 to 5 feet higher than the lands lying between the river and the bluffs, which is usual in alluvial streams. Approximate channel capacities of the river at key locations, Shelbyville (mile 220.4), Vandalia (mile 160.8), Carlyle (mile 105.7), and New Athens (mile 40.9), are 4,500 cfs, 5,000 cfs, 7,000 cfs, and 8,500 cfs, respectively. The river channel has a slope of about 0.10 foot per mile between miles 0 and 23, 0.70 foot per mile between miles 23 and 107, 0.80 foot per mile between miles 107 and 155, 1.34 feet per mile between miles 155 and 222, and 1.65 feet per mile between miles 222 and 325.

[1]Hydraulic Engineer, Lower Mississippi Valley Division

The temperature of the Kaskaskia River Basin is moderate, the mean annual temperature being about 55 degrees F. The average annual precipitation over basin is 39.0 inches. The history of the Kaskaskia River Basin indicates that it has been subjected to frequent floods. These floods have usually occurred during the spring or early summer. The area subject to flooding above Shelbyville is small. The approximate floodplain area, in acres, downstream of Shelbyville is as follows:

Location	Cropland	Non-Cropland	Total
Between Shelbyville and Vandalia	33,390	10,980	44,370
Vandalia and Carlyle	23,580	19,110	42,690
Below Carlyle	33,950	50,970	84,920

DESCRIPTION OF AUTHORIZED PROJECTS

The Shelbyville and Carlyle Reservoirs and agricultural levees on the Kaskaskia River, Illinois, were authorized in 1958 as projects in a plan for flood control and related purposes. The plan of improvement for the Kaskaskia River consists of a dam and reservoir at mile 221.8 (near Shelbyville), six levee districts between Shelbyville and Vandalia, a dam and reservoir at mile 107 (near Carlyle), five levee districts below Carlyle, and protection for the town of New Athens (mile 41). The flood control plan was devised as one integrated system of reservoirs in joint operation and in combination with the levees for flood protection to agricultural areas.

The Kaskaskia River Navigation Project was authorized in 1962 to provide a comprehensive plan for navigation on the lower portion of the Kaskaskia River. Releases, as required for Kaskaskia River navigation, will be made from the joint-use storage pools of the Shelbyville and Carlyle Reservoirs to augment low Kaskaskia River flows for lockage purposes.

Reservoirs. The reservoirs are multiple-purpose projects, consisting of storage allocations for flood control and the joint-use purposes of navigation water releases, water supply withdrawals, and low-water releases for downstream water quality control. Their drainage areas are 1,030 square miles above Shelbyville Dam and 2,680 square miles above Carlyle. The Shelbyville Reservoir has a storage capacity of 684,000 acre-feet below the top of the flood control pool of which 474,000 acre-feet or 8.63 inches of runoff are for flood storage. Outflows from Shelbyville Dam will enter Carlyle Reservoir approximately 62 river miles downstream. The Carlyle Reservoir has a storage capacity of 983,000 acre-feet below the top of the flood control pool of which 700,000 acre-feet or 4.90 inches of runoff are for flood storage.

DESIGN FLOODS

Shelbyville Reservoir. The flood control storage of the Shelbyville Reservoir is based on a standard project flood, which is expected to occur once in more than 100 years. The flood is based on rainfall of 13.16 inches and a runoff equivalent to 9.85 inches, including base flow. The peak discharge at damsite was determined to be 77,000 cfs, and peak reservoir inflow to be 165,000 with maximum regulated outflow of 4,500 cfs. The maximum flood of record by volume (January - February 1950) would utilize 53 percent of the flood control storage.

Carlyle Reservoir. The initial allocation of flood control storage for the Carlyle Reservoir was based on the maximum flood (volume) of record, which occurred in December 1949 to March 1950. The selection of this flood for design was based on the Carlyle Reservoir serving alone since the Shelbyville Reservoir was still not authorized at the time of its selection. The design flood had a runoff volume equivalent to 13.32 inches, including base flow, and made full use of the flood control storage in excess of the maximum regulated release of 7,000 cfs. The peak inflow for the design flood amounted to 40,700 cfs. In comparison, the standard project flood peak under natural conditions amounted to 77,000 cfs at Carlyle. The peak reservoir inflow was was determined to be 105,000 cfs, with a total runoff volume equivalent to 8.10 inches, including base flow. It has been determined that the standard project flood runoff in excess of 7,000 cfs regulated release could be contained in the flood control pool. Under the basin development plan including the Shelbyville Reservoir, the Carlyle flood control storage will be reduced by converting some of the storage to joint-use purpose (navigation storage). After conversion, the period of record routing resulted in the maximum pool level 1.1 foot below top of flood control pool.

RESERVOIR REGULATION

Shelbyville Reservoir. The flood control pool was divided equally into two zones. It was contemplated that in the lower zone, a minimum release of 10 cfs would be maintained at all times while the maximum release would be 4,500 cfs. Within the limits of the zone, the operation would be as follows: While at zone bottom elevation, the release would equal inflow but not greater than 4,500 cfs nor less than 10 cfs. While within the zone, the release would normally be 4,500 cfs but reduced to 1,000 cfs if the Mississippi River reaches flood damage stage at either Chester or Cairo. In the upper zone, a release of 4,500 cfs would be maintained at all times.

Carlyle Reservoir. During the interim period before Shelbyville Reservoir becomes operable, the authorized plan of regulation is based on all flood control storage (900,000 acre-feet or 6.3 inches of runoff) reserved for storage of flood runoff in excess of 7,000 cfs release. Before the construction of Shelbyville Reservoir is completed, this storage will be revised for joint operation of the two reservoirs.

STATUS OF PROJECTS

Construction on the Shelbyville Reservoir was initiated in 1963 and scheduled for completion during Fiscal Year 1970. The construction of the Carlyle Reservoir project was initiated in 1958 and was completed in Fiscal Year 1967. Construction of the navigation project began during Fiscal Year 1966 and is scheduled for completion during Fiscal Year 1972. Construction of the New Athens project was initiated during Fiscal Year 1965 and was completed during Fiscal Year 1967. No construction work has been initiated on any of the agricultural levee projects. Only recently has detailed planning been initiated for two of the eleven levee projects.

PROBLEMS INVOLVED IN OPERATION STUDIES

A problem of inadequate channel capacity to continue operation of reservoir projects as planned on the Kaskaskia River, Illinois, developed early in the operational stage of Carlyle Reservoir. An investigation of a downstream area where complaints of flooding due to project releases were received from landowners confirmed the adverse condition. A similar situation is anticipated below Shelbyville Reservoir.

The plan of improvement for the river provided for an integrated system of levees and reservoirs for local flood protection and other purposes. The damage area was due to be protected by levees under the plan. Of the eleven authorized agricultural levee units of the plan, all but two are inactive due to a lack of local interest and support. The plan contemplated that the levee units could be constructed first with little adverse effects, and the reservoirs later. It did not consider the present situation of the reservoirs only completed. Since most of the levee projects are inactive, it is reasonable to consider the river as a regulated system consisting of upstream reservoirs as the only means of protecting downstream areas. A solution to the problems therefore involves studies of the regulated system to fully define the extent of the damage areas; consider all possible means in conjunction with reservoirs to alleviate the damages and determine an economical plan for remedial measures.

The need to allay the complaints of flooding and at the same time seek a solution, suggested an interim solution pending a long-range solution. Interim solutions involve the present operational stage of Carlyle alone and the near future stage of Carlyle and Shelbyville in joint operation. For each stage, a best plan of regulation designed to minimize downstream damage is the desired objective. Reservoir operation studies of several plans of regulation were made for selection of the best plan. Regulation plans were developed from limited investigation of the downstream and reservoir areas. A study based on these data suggested requirements of the plan as to downstream releases and upstream pool area and storage.

For an ultimate solution to the problems, a comprehensive study of the river as a regulated system will be necessary. An optimum plan of regulation will be determined. The plan will include the Carlyle and Shelbyville Reservoirs, considering downstream channel conditions and improvements to minimize damage, with the requirement of storage reserved for the Kaskaskia River Navigation Project.

TECHNIQUES CURRENTLY IN USE

Carlyle Reservoir Operating Alone. The urgent need to reduce the project release to a nondamaging release as early as practicable did not allow for refining the technique used for developing a satisfactory plan of regulation. The technique consisted of analyzing the requirement of the downstream conditions with regard to nondamaging releases, then determine a plan of regulation that would best serve the downstream requirement without interfering with the upstream reservoir design requirements. Investigations of the downstream damage area revealed the following facts. The area extends 18 miles below the dam to the first major tributary. The nondamaging release is 4,000 cfs as contrasted with the originally planned 7,000 cfs. Operation studies of routing floods of record under a regulation plan with a maximum release of 4,000 cfs showed that the design flood storage would be exceeded twice during the period of record, resulting in unacceptable spillway releases. The upstream requirements, in addition to the reservoir design storage, include damages to easement and recreation areas because of higher pool stages induced by reduced downstream releases. Knowledge concerning the growing season established the time of year when reduced nondamaging releases were needed. Available data on upstream and downstream stage-area-damage were supplemented with up-to-date data as necessary. With the above information, it was a simple matter to develop a technique of study to minimize the downstream damages. Plans of regulation for operation studies were established rather arbitrarily in which the flood control pool was divided into zones for scheduling releases. The lower zone for nondamaging releases; the upper zone for larger releases, which were gradually increased, as required, so that no flood of record would cause the design storage to be exceeded. The amount of storage in the lower zone was also arbitrarily established. The amount was varied by months, a minimum during months of the flood seasons and a maximum during the growing season. Several variations of the above plans of variable releases, together with the approved plan (7,000 cfs release) and a nondamaging release plan (constant 4,000 cfs release) were studied initially. Preliminary reservoir routings were made to find the best of the variable release plans for further study. Two major floods were routed, and the plan selected attempted to optimize the shortest maximum release duration, smallest maximum outflow, and the lowest pool elevation. The variable release plan and the constant release plans were studied in greater detail. Reservoir and downstream routings of the floods of record under each of the three plans were made. An economic evaluation of the results of routings, considering upstream and downstream damages, showed that the variable release plan produced the least annual damages of the plans studied, and this plan was adopted.

Joint Operation of Carlyle and Shelbyville Reservoirs. A satisfactory plan for the joint operation of the two reservoirs involves consideration of multipurpose features of each reservoir. This is in addition to the requirements established for the Carlyle-only plan, which now apply to both reservoirs and consequently involve four damage areas. Investigation of Shelbyville downstream area revealed the following facts. The area of potential damage due to reservoir releases extends 35 miles below the dam. The nondamaging release was determined to be 1,800 cfs. This release contrasts with the maximum design release of 4,500 cfs to control the reservoir design flood, i.e., the Standard Project Flood.

At this time, the studies are in progress. Information available on the conduct of the study indicates that procedures are similar to those used for Carlyle alone but more extensive, in order to more nearly develop an "optimum" plan. It should be noted that in this phase of the study, joint operation is an expression for independent plans of operation for each of the reservoirs in consideration of the upstream and downstream requirements of each independently. However, since the Carlyle area includes Shelbyville, operation plans of Shelbyville exert an influence on Carlyle's plan. The optimum joint operation plan would then be the best of the combination of independent regulation plans to reduce and equitably distribute the damages among the four potential damage areas.

To initiate the study, a variable release plan for each reservoir was selected for further study based on preliminary evaluations of the method of regulation previously described for the Carlyle study. Detailed studies were begun. The plan of study consisted of a series of trial regulation plans whereby each one was evaluated. The initial basic regulation plan (Plan I) was utilized for the period of record routing study. The results of the routing study were analyzed hydraulically and economically. An envelope of storage hydrographs was developed for each reservoir to determine seasonal pool limits. The results of this first plan of regulation were studied to determine type and location of major damages, as well as the date of occurrence. This information was then used to determine any changes in the first plan of regulation which might be necessary to reduce the potential damages. The variables modified by the trial and error procedure were pool stage and discharge, as related to month of year. This revised plan subsequently became Plan II. Average annual damages were then computed for this second plan. This procedure continued until the optimum regulation plan was obtained for the joint operation of Carlyle and Shelbyville Reservoirs.

In the course of the analysis, it was found that even the most suitable plan could be improved upon by dropping the requirement for storage of navigation water, thereby gaining more flood control storage. Therefore, two regulation plans may be recommended, an interim plan for use until the navigation project is operational, and a long-range plan to be used after the navigation project becomes operational (estimated year 1974). The

interim plan is characterized by winter drawdowns of the reservoir level between December and April. The pool drawdowns before the completion of the navigation project are permissible since the hazards of a severe drought depleting the reservoir are greatly reduced because navigation releases are not required. The long-range plan takes into account navigation requirements and assures navigation water storage as well as water supply storage during the severest drought of record.

Using the trial method of analysis and the 33-year period of record, nine plans of regulation were studied in an effort to determine which method of regulating the two reservoirs resulted in the least damage and was the most feasible plan based on hydrologic considerations. The plans were all fundamentally the same in the general scheme of release. Various alterations were made to the joint-use pool elevation, recreation damage elevation, flood control release, months for winter flood control release, and winter drawdown elevation.

Economic analysis was used, in the course of the study, to evaluate the possibilities for improvement of each successive plan of regulation. Flood dates and acreage flooded were utilized to determine average annual damages which would have resulted, during the period of record, from the regulation of the dams under each of the successive plans of operation. Because of differences in farming practices and concentration of farmland and property, it was necessary to divide the damaged acres into four study areas. This was also necessary because of differing sources of damage; pool stage in some cases, and discharge in others. Efforts to alleviate damages in one area will usually increase damages in one or more of the other areas because of the inverse relationship between pool stage and discharge. Therefore, the objective of the study was to develop a plan of regulation which is hydraulically feasible and minimizes total damages, while maintaining an equitable distribution of various types of damages among the given geographic areas.

It should also be mentioned that a substantial amount of the flood damage to recreation was caused by only five flood events which occurred at the peak of the recreation season. Because of the above described situation, it may be advisable to present, for information purposes, the average annual damage to property and crops alone, thus isolating the aesthetic loss due to the impact of recreation damages.

It may be practicable to have two plans of regulation for Carlyle and Shelbyville Reservoirs together. One of the plans could be used as an interim plan of regulation, until the navigation project becomes operational, and the other as long-range plan of regulation, thereafter.

Other Considerations. In actual reservoir operation, detailed release schedules will be developed to obtain additional downstream and upstream benefits, but their influence on the comparison of plans made herein is

not significant. These are cutbacks in releases from the normal scheduled release to attenuate downstream flood crests and continuing releases at the maximum attained for a given flood for rapid drawdown where the gradual reduction in releases under the variable release plan would serve no useful purpose.

FUTURE NEEDS

The comprehensive study of the river system will consider all possible solutions to increase the beneficial influence of the upstream reservoir projects on the downstream agricultural areas. studies of regulation plans in conjunction with downstream channel conditions and improvements will be made to determine an optimum coordinated plan of regulation to minimize or eliminate damages due to reservoir projects. In accordance with present techniques, the study will generally fall into two parts: a comparison of alternative plans of operation based on natural downstream conditions and similar comparison of these plans with improved downstream conditions.

The available physical data on topography and extent of agricultural developments are inadequate for the needs of this study. The flat topography of the floodplain areas makes possible large change of flooded areas for moderate change in controlled releases. Detailed mapping appears to be necessary and is under consideration. The mapping will be costly, as it includes reaches of about 60 river miles below the Shelbyville Dam to the head of Carlyle Reservoir and about 55 river miles below Carlyle Dam to the head of the navigation project. Additional stream gaging in the downstream floodplain reaches is needed. Comprehensive economic investigations will be necessary.

A major consideration in programming the hydrologic study will be the method of study of the reservoir regulation plans in conjunction with the downstream channel improvements to determine optimum channel size. Whether the trial method will be too cumbersome is not known at this time. An outline of the hydrologic and hydraulic study follows:

1. Develop discharge rating curves for the downstream end of each reach to be studied.

2. Determine valley elevation versus area and storage curves.

3. Determine inflows to reservoirs and local runoff below dams.

4. Select the various alternative plans of operation and make preliminary analysis using two or three major flood periods.

5. Select the four or five best plans and prepare period-of-record reservoir routings (Carlyle and Shelbyville in operation).

6. Perform routing studies for the four best plans and the authorized plans of Carlyle and Shelbyville releases and local runoff through the natural downstream reaches.

7. Select the best plan and perform routing studies for it and the authorized plans, for three alternative improved channel plans (7,000, 6,000, 5,000 cfs) for Carlyle and (4,500, 3,600, 2,700 cfs) for Shelbyville.

8. Plot stage hydrographs for each downstream reach for the recommended plan and prepare other plates for presentation in the report.

9. Prepare text of report.

The experience gained from the study of the joint-operation plan for the reservoirs will aid in programming the study. As the joint-operation plans consisted of independent plans, there will be a need to coordinate the independent regulation plans to develop an optimum coordinated regulation plan for the reservoirs. Methods of coordinating releases have not been developed. Better use of the available storage of the system will result, and increased benefits due to operation plans.

An unusual aspect of this study is its relation to the authorized plan of improvement. The plan of improvement provides for reservoirs and downstream levees. Channel improvements are authorized for the plan of improvement but only in conjunction with and as part of construction of the levee projects. Additional authorization may be necessary to consider channel improvements without the levees. Should the channel improvements be completed and the levee projects activated, then the regulation techniques developed as a result of this study will be useful in hydrologic studies for the levee design.

SUMMARY OF DISCUSSION

Compiled by H. O. Reese[1]

In response to questions raised, it was indicated that channel capacities on the Kaskaskia River may have been over estimated during preauthorization studies. This problem is common throughout the Corps of Engineers. Many times it is found after reservoirs are initially placed in operation that downstream channel capacities are less than what was considered in design and operation studies. Another common problem is that encroachment by local interests on downstream floodways takes place after projects are completed and placed in operation. This particularly may occur if there is no necessity during the first years of operation to make releases equal to downstream channel capacities.

It was suggested that future studies on the Kaskaskia River system should evaluate the feasibility of obtaining flowage easements downstream of the reservoir projects. Mr. Pinner indicated that this alternative solution is being considered. However, at this time it does not appear to be a feasible solution.

Peaking effects on flood hydrographs that sometimes occur from increases in flood travel time and loss of valley storage due to levee construction were discussed.

Problems associated with multistage development of reservoir projects were discussed. Local interests who become accustomed to certain prevailing conditions that exist for the initial stage of development generally object to any change that appears to jeopardize their fishing and recreation. The initial operating schedule establishes a precedent that is sometimes rather difficult to change at a later date.

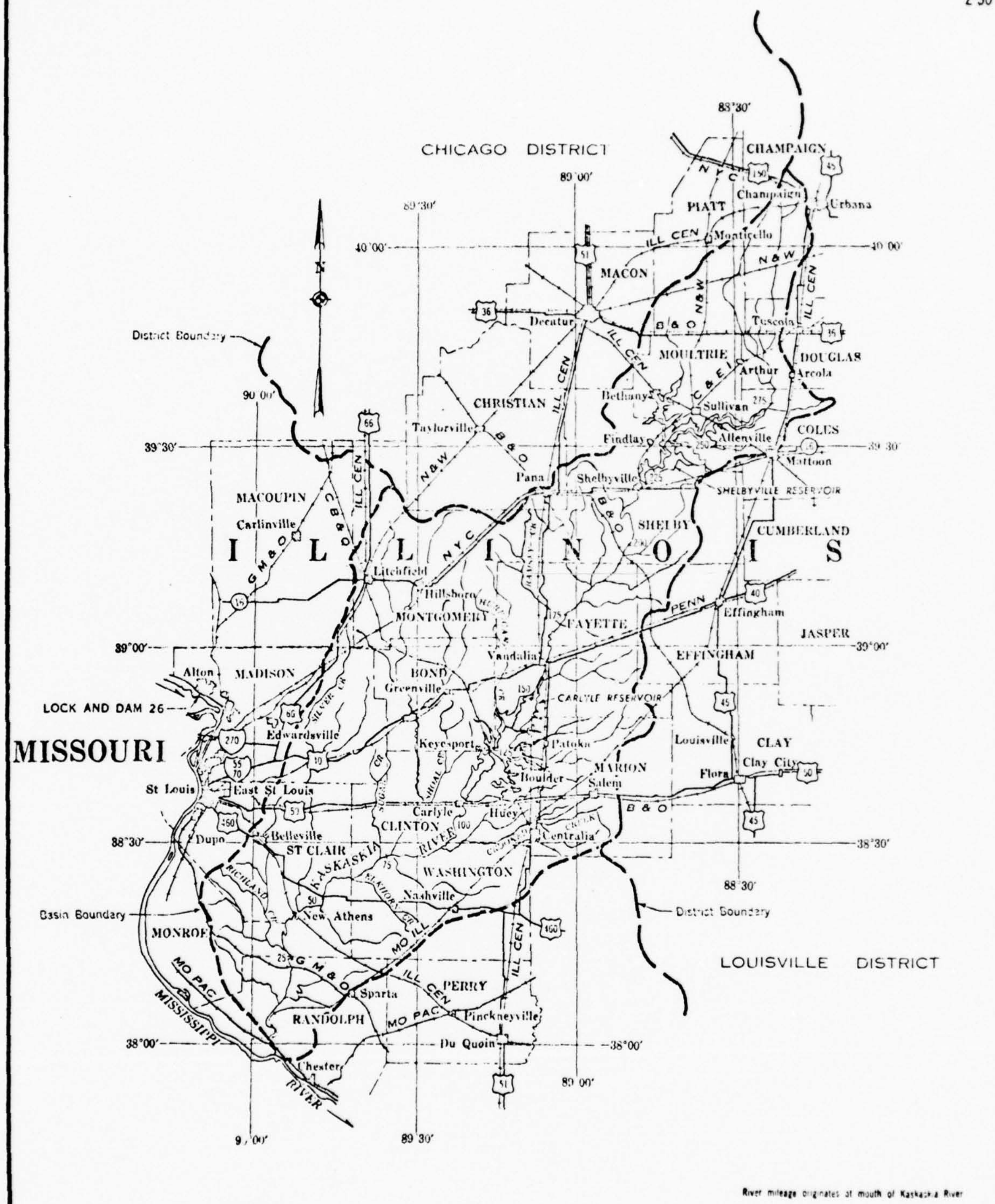
The following two objective functions in regard to optimization of flood control benefits were discussed and compared:

1. Operate to reduce flood damages at each damage area on a equitable basis.

2. Operate to minimize the overall total flood damages, even though one area may have little flood protection and another area may have nearly full flood protection.

It was concluded that both objective functions should generally be considered in the light of authorization provisions and changing conditions.

[1]Chief, Special Assistance Branch, The Hydrologic Engineering Center



FLOOD CONTROL PROJECT
KASKASKIA RIVER
BASIN

SCALE IN MILES
12 0 12 24

U. S. ARMY ENGINEER DISTRICT, ST. LOUIS
CORPS OF ENGINEERS
ST. LOUIS, MISSOURI
JUNE 30, 1969

SYSTEM OPERATION OF RESERVOIRS ON THE APALACHICOLA RIVER

by

R. A. Eckstine[1]

The Mobile District is just taking the first step in developing a system operation for some of its reservoirs. A system operation was not developed sooner because the District comprises several entirely separate and unrelated river systems; and the nature and location of the earlier reservoir projects were such that systems operation was not feasible. The Pearl River (see plate 1) has no Corps of Engineers reservoir projects. In the Pascagoula River basin there is one small flood-control reservoir on a headwater tributary. The Tombigbee-Warrior River has been developed for many years with a series of locks and dams for navigation from Mobile to Birmingham, Alabama, a distance of about 350 miles, but none of the reservoirs have any usable storage.

On the Alabama-Coosa River system, the largest in the District with a drainage area of 22,800 square miles, there is one Corps of Engineers reservoir project in operation. Allatoona Dam, completed in 1949, is a power and flood-control project located on a headwater tributary of the river system. Another flood control and power project, Carters Dam, is under construction on an adjacent headwater tributary. These headwater tributaries combine about 50 miles below Allatoona and about 75 miles below Carters to form the Coosa River, which has been completely developed throughout its entire 286 mile length by a series of six reservoirs built by the Alabama Power Company, a privately owned utility. Three of these dams are operated for flood control under regulations established by the Corps of Engineers, but all power releases, except as they might be limited by flood control requirements, are scheduled entirely by the power company. Most of the drainage area of the Tallapoosa River, which combines with the Coosa to form the Alabama River, is also controlled by Alabama Power Company dams. The Mobile District is presently developing the Alabama River for navigation by constructing three locks and dams, two of which will have power plants. None of the three have any usable storage and most of the inflow into the upper reservoir is controlled by releases from the power company's dams.

The other principal river system in the Mobile District is the Apalachicola. The developments on this river are such that a systems operation is feasible, and flow requirements for navigation have made a systems operation very desirable.

[1]Chief, Reservoir Regulation Section, Mobile District

The Apalachicola River system, made up of the Chattahoochee, Flint, and Apalachicola Rivers with their tributaries, drains an area of 19,200 square miles, including portions of northern and western Georgia, southeastern Alabama and a strip through the western extension of Florida. The length of the basin, which extends from the Blue Ridge Mountains to the Gulf of Mexico at Apalachicola Bay, is 385 miles. Its greatest width is 110 miles and its average width is about 50 miles. The Apalachicola is the farthest east of the major river systems emptying into the Gulf of Mexico.

The Apalachicola River, the stem of this system, lies wholly within the Coastal Plain and is formed by the confluence of the Flint and Chattahoochee Rivers at the southwest corner of Georgia. It is 108 miles long with major widths of 600 to 800 feet. The average annual runoff from the entire Apalachicola watershed is 17 inches, which yields 17,400,000 acre-feet at the average rate of 24,000 cfs.

The Flint River rises just south of Atlanta, Georgia, and flows for about 350 miles in a southerly direction, curving to the west to join the Chattahoochee River at the southwest corner of Georgia. Its drainage basin extends 215 miles from north to south with an average width of about 40 miles, and has an area of 8,500 square miles. The annual runoff from the Flint River basin is 16 inches which produces an average discharge of 9,800 cfs.

The headwater streams of the Chattahoochee rise in the Blue Ridge Mountains of north Georgia near the western-most tip of South Carolina. The river flows in a southwesterly direction for a distance of 235 miles to West Point, Georgia, on the Alabama-Georgia line. Turning south at this point, it continues for about 200 miles to its mouth, constituting the boundary between Georgia on the east and Alabama and Florida on the west. The 8,650 square-mile drainage basin is 310 miles long with an average width of 28 miles and a maximum width of 55 miles. Annual runoff from the Chattahoochee basin is 18 inches and the average discharge 11,500 cfs.

Rainfall over the Apalachicola basin averages 53 inches annually, varying from about 61 inches over the mountain section of the upper reaches to 50 to 52 inches over the middle portion and increasing again to 55 inches over the Gulf Coast area. Although the rainfall is fairly well distributed throughout the year, there is some seasonal variation, with the heaviest rains usually occurring in the winter and the lightest during the fall. The annual average runoff of 18 inches is 34 percent of the rainfall. The average runoff varies considerably with the seasons, being high during the winter and early spring and low in late summer and fall.

Existing Corps of Engineers developments in the Apalachicola basin consist of the following projects:

1. Jim Woodruff Lock and Dam, located just below the point where the Chattahoochee and Flint Rivers unite, is a multiple-purpose project, designed principally to provide for navigation on the Apalachicola, Chattahoochee and Flint Rivers and to produce hydro-electric power. The 108 miles of open river channel between the dam and the Gulf of Mexico has a total fall of about 40 feet, and navigable depths are dependent on a continuous flow. Therefore the Woodruff power plant operates as a run-of-river project utilizing up to 2 feet of pondage for reregulating the inflow, which is subject to considerable variation caused by the operation of upstream power plants.

2. Columbia Lock and Dam on the Chattahoochee River, 47 miles upstream from Jim Woodruff, is a navigation project. It has a maximum lift of 25 feet and no usable storage.

3. Walter F. George Lock and Dam, 28 miles upstream from Columbia, is a multiple-purpose power and navigation project. It has a maximum static head of 88 feet and 244,000 acre-feet of seasonally available storage.

4. In the headwaters of the Chattahoochee River, 274 miles upstream from the Walter F. George project, is Buford Dam, a multiple-purpose flood control and power project. It has 1,050,000 acre-feet of usable storage below the top of the power pool.

In addition to the Corps of Engineers projects on the Chattahoochee River there is a series of privately owned power dams, most of which belong to the Georgia Power Company. These occupy a 38-mile reach of the river just above the upper end of the reservoir formed by the Walter F. George Dam. This section of the river crosses the Fall Line, which is the geologic boundary between the recent and poorly consolidated sediments of the Coastal Plain and the hard, crystalline rocks of the much older and higher Piedmont Plateau. The total operating head developed by the projects in this 38-mile reach is 360 feet. One of the reservoirs formed by these dams has a usable storage of 120,000 acre-feet; the others have varying amounts of pondage. These are all operated under licenses issued by the Federal Power Commission, and the Corps has no jurisdiction over their operations.

On the Flint River there are two privately owned power dams. One of these, 104 miles above the Jim Woodruff project, is owned and operated by the Georgia Power Company and the other 30 miles further upstream belongs to a county authority. The Corps has no jurisdiction over the operation of either of these dams; however, they have only a limited amount of pondage and have no appreciable effect on the flows into the Jim Woodruff Reservoir.

The project authorization for improvement of the Apalachicola River called for dredging and snagging to provide a navigable channel 9 feet deep at a low water flow of 9,300 cfs. Studies showed that a flow of 9,300 cfs could be expected 95 percent of the time and that the expected minimum flow of 7,300 cfs would provide a channel 7 feet deep.

After the initial dredging of the 9-foot channel it was found to be impossible to maintain project depth throughout the low-flow season, June to December, each year. Depending on the status of maintenance dredging at the time, flow requirements to maintain a 9-foot channel vary from about 13,000 cfs to 17,000 cfs. As flows decrease, the draft of tows must be reduced accordingly. The result has been that navigation interests have made continuing demands for releases from the Buford storage that are considerably in excess of the flow requirements to meet power contract commitments.

In order to provide a sound water management program which would assure maximum releases from storage at Buford and Walter F. George for benefit of navigation without jeopardizing the projects' capability to meet power contract requirements, a system operation study was made. The study was based on 40 years of discharge records, which included two severe drought periods.

The system operation plan established zones within the storage prisms at Buford and Walter F. George, which indicate the maximum flow that can be maintained in the Apalachicola River by storage withdrawals for any given level in the two storage reservoirs. All releases are made through the power plants and all power scheduling is on a weekly basis. Full use is made of almost 2 feet of pondage in the Jim Woodruff Reservoir to compensate for inaccuracies in inflow estimates and unanticipated changes in releases from the privately owned upstream power plants. Withdrawals from the Woodruff pondage are replaced as required from the storage in Walter George. Withdrawals from Walter George are replaced wholly or in part by releases from Buford, depending on what the system study shows to be the proper balance to be maintained between the two reservoirs at that time.

As was mentioned earlier, previous studies had indicated that with the existing improvement a flow of 9,300 cfs could be expected 95 percent of the time. The system analysis shows that this flow, which with proper maintenance dredging will provide 7 to 7.5 feet of water in the channel, can be maintained 100 percent of the time. While this does not provide project depths of 9 feet, as the original design studies anticipated, it does permit year-around navigation at depths which are profitable for the operators.

Problems associated with a system operation in the Apalachicola River basin are mostly caused by the distance from Buford, the principal storage reservoir, to the Walter George Reservoir; and regulation by the privately owned power dams between the two projects. Travel time from Buford to George is usually 3 to 4 days, and this is sometimes extended by several more days by reregulation through the private power dams. This means that the need for special releases from Buford must be anticipated by at least a week. Sometimes after a release has been made, rainfall over the intervening area makes the release not only unnecessary but in some cases undesirable.

This problem will be at least partly solved with the completion of another reservoir now being constructed by the Corps on the Chattahoochee River between Buford and Walter George Reservoirs. The storage in West Point Reservoir, a power and flood control project located just upstream from the private power dams, will not only increase minimum flows for navigation but will also permit better control of special releases from Buford.

In developing the system operation plan for the Apalachicola River, flood control was not taken into consideration. Flood control operations at Buford and Allatoona are independent of other project functions. The power contract allows for complete shut-down of either or both projects whenever necessary to alleviate downstream flooding. This has no effect on the system operation for navigation, the purpose of which is to provide increased flow during low-flow periods.

Another factor in reservoir systems operation in the Mobile District that needs mentioning is the interrelationship of power operations at some of the projects. The district has four power plants operating at the present time: Allatoona in the Alabama-Coosa basin and Buford, George and Woodruff in the Apalachicola basin. Woodruff is operated strictly as a run-of-river plant and all of the energy goes to the Florida Power Corporation. All of the energy from Allatoona and Buford and most of the energy from George goes to Georgia Power Company under a single contract negotiated and administered by the Southeastern Power Administration. Neither the Corps nor Southeastern Power Administration has any distribution lines, so that power from all projects is delivered to the customers at the switch-yard. The contract requires certain minimum amounts of energy and capacity to be delivered to the customer each week. The weekly requirements vary from month to month throughout the year.

In developing the system operation plan for the Apalachicola River, the Allatoona project was included in the study as part of the power system. Although the Allatoona storage adds nothing to navigation flows on the Apalachicola River, having it in the power system permits greater flexibility in scheduling releases from Buford and George for benefit of navigation.

The system operation plan for the Apalachicola River is aimed principally at providing optimum flow conditions for navigation throughout the low-flow season each year. These releases for navigation are sufficient to meet all contract commitments for power. At present, when there are no requirements for special releases for navigation and reservoir levels are not critical, the weekly power requirement specified by the contract is divided among the three projects on a percentage basis. Consideration is being given to modifying the plan to include power plant efficiency as a factor in determining the percentage of the weekly power commitment to be carried by each plant during those periods when navigation requirements are not controlling.

It was mentioned earlier that the completion of West Point Dam will alleviate some of the problems that are now encountered in the system operation of the Apalachicola River reservoirs. Additional future development in the basin includes three storage reservoirs, which have been authorized for construction on the Flint River, and when they are completed, the low-flow conditions on the Apalachicola can be further improved. It is expected that power from West Point and the three Flint River projects will be sold under the existing contract with the Georgia Power Company. This would permit maximum flexibility in scheduling power releases from all plants in the Apalachicola River basin in such a way that the best interests of navigation will be served.

When projects under construction in the Alabama-Coosa River basin are completed, there will be two headwater storage reservoirs and a navigation project on the lower river consisting of three locks and dams, two of which have power plants. A system operation plan for this basin will be desirable, but at present it has not been determined how a meaningful plan can be developed with six privately owned reservoirs separating the Corps' storage reservoirs from the lower river development. This is a problem that will require further investigation.

Present thinking by Southeastern Power Administration is that the power from all Mobile District power projects except Jim Woodruff will be sold under one contract. In addition to the Mobile District projects, the present contract also includes two projects in the Savannah District. This means that consideration must be given to developing a system operation plan which would include all of these power plants as a single power system and at the same time provide optimum flows for navigation on the three river systems involved.

SUMMARY OF DISCUSSION

Compiled by H. E. Kubik[1]

The author was questioned on the nature of coordination with the private power companies in determining the releases necessary from the Corp's projects. Daily contact is maintained with the private power companies. The several private power plants that exist between the Corp's projects can significantly change the predicted inflow at the downstream project. The private power companies can be asked to pass upstream releases if the water is needed for immediate use downstream.

There was some discussion of the need for reregulating structures below hydropower reservoirs. Buford and Allatoona Reservoirs are operated primarily for peaking capability, and no reregulating structures have been built. A reregulating dam is being built below the Carters Dam which is now under construction.

There was a question as to whether the operating criteria of the private companies have changed during the system analysis studies. It is difficult to estimate how the private plants may be operated. The contract between the private power companies and the Southeastern Power Administration stipulates that the Corps will estimate the power that can be guaranteed on a weekly basis. This causes considerable variation in generation at the private plants, since they are used to meet the remaining fluctuating power load.

There was general group discussion of the operational problems that result because the power contracts are negotiated by other federal agencies. Mr. Midkiff reported that the private power companies are given much flexibility in establishing the operation of the Corps reservoirs, even to the point of loading and unloading the units at the project. Mr. Lewis indicated that over a season the Columbia River basin, with its many power producers, is operated nearly as efficiently as if it were under one ownership. Mr. Davis thought the situation causes some duplication of effort, especially in hydrologic studies. Also several of the contracts were subject to political rather than hydrologic constraints. Mr. Carlson and Mr. Lewis agreed that interties of large power systems can cause problems, because large power demands located at a remote distance from the power source tend to look at only maximum power capability rather than also considering local needs such as fish and wildlife, recreation, water quality and other requirements.

Mr. Beard suggested that, to the extent that division of responsibility precludes the optimization of an overall system (such as a power system that serves an entire region), development of best operation plans is handicapped, because one is required to optimize a part of a system only, when that part cannot logically be segregated from the entire system.

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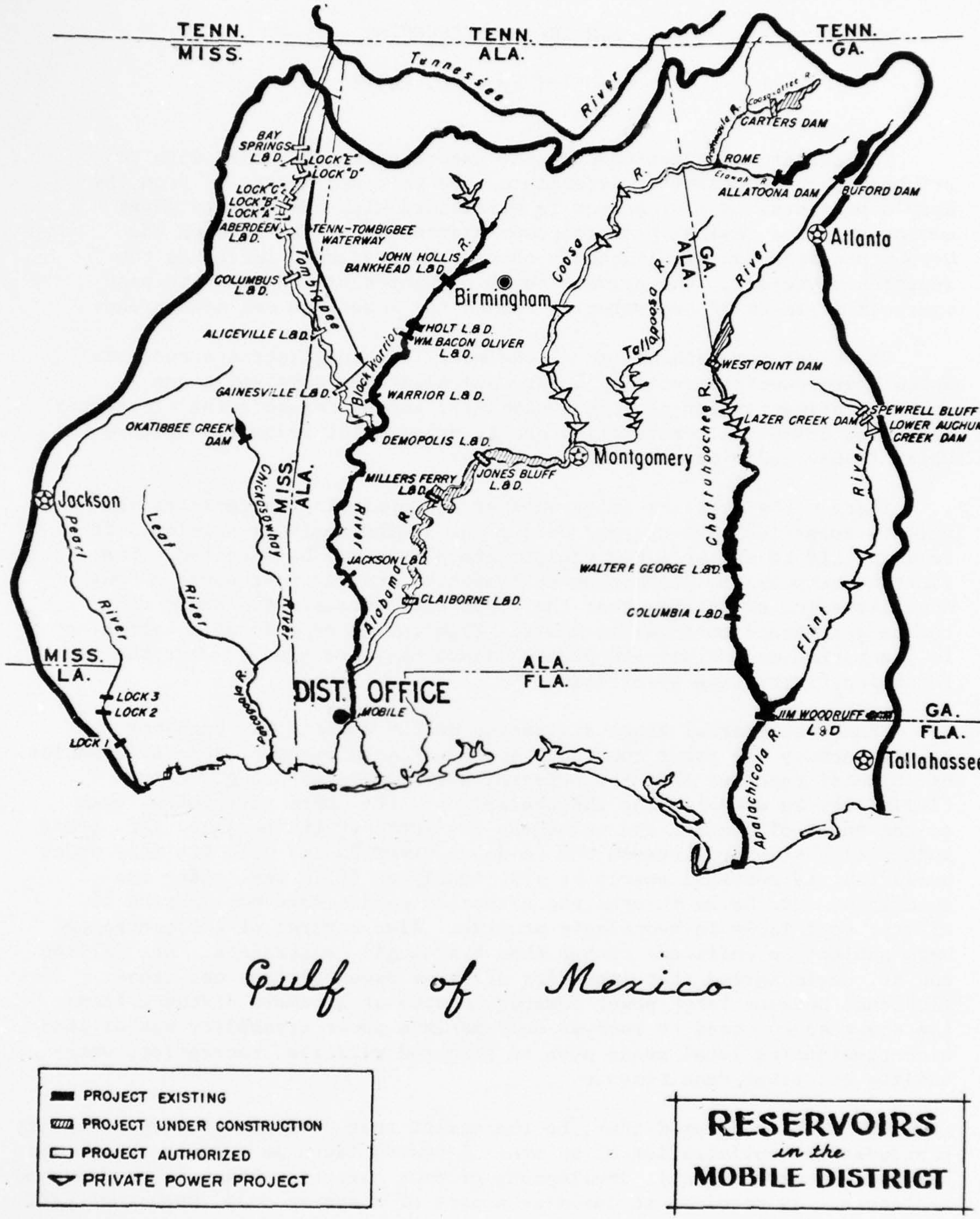
TENN.
MISS.
TENN.
ALA.
TENN.
GA.
Tennessee River
BAY SPRINGS L.& D.
LOCK "E"
LOCK "D"
LOCK "C"
LOCK "B"
LOCK "A"
ABERDEEN L.& D.
TENN-TOMBIGBEE WATERWAY
COLUMBUS L.& D.
Tombigbee
JOHN HOLLIS BANKHEAD L.& D.
Birmingham
ALICEVILLE L.& D.
Black Warrior R.
HOLT L.& D.
WM. BACON OLIVER L.& D.
GAINESVILLE L.& D.
WARRIOR L.& D.
OKATIBBEE CREEK DAM
DEMOPOLIS L.& D.
Coosa R.
Tallapoosa R.
Montgomery
JONES BLUFF L.& D.
MILLERS FERRY L.& D.
Jackson
Pearl River
Leaf River
Chickasawhay River
MISS.
ALA.
River
Alabama R.
JACKSON L.& D.
CLAIBORNE L.& D.
MISS.
LA.
LOCK 3
LOCK 2
LOCK 1
Pascagoula R.
DIST. OFFICE
MOBILE
ALA.
FLA.
CARTERS DAM
Oostanaula R.
Coosawattee R.
ROME
Etowah R.
ALLATOONA DAM
BUFORD DAM
Atlanta
GA.
ALA.
River
WEST POINT DAM
LAZER CREEK DAM
SPEWRELL BLUFF DAM
LOWER AUCHUMPKEE CREEK DAM
Chattahoochee R.
Flint River
WALTER F. GEORGE L.& D.
COLUMBIA L.& D.
JIM WOODRUFF L.& D.
GA.
FLA.
Apalachicola R.
Tallahassee
Gulf of Mexico
PROJECT EXISTING
PROJECT UNDER CONSTRUCTION
PROJECT AUTHORIZED
PRIVATE POWER PROJECT
RESERVOIRS in the MOBILE DISTRICT

PLATE 1

RESERVOIR OPERATION FOR CONSERVATION ON ROANOKE RIVER

by

James W. Midkiff[1]

DESCRIPTION OF THE BASIN

Natural Features. The Roanoke River Basin is located in southern Virginia and northern North Carolina as shown on figure 1. It extends 220 miles from the eastern slopes of the Appalachian Mountains to Albemarle Sound. The width of the basin varies from 10 to 75 miles. Total area of the watershed is 9,580 square miles.

The average annual precipitation over the basin is 43 inches with annual extremes of 27 and 56 inches. Flood producing storms occur in all seasons of the year but runoff is normally higher in the winter and spring than in the summer and fall. In the late summer and fall, intense rainfall sometimes occurs with the passage of a tropical hurricane. The average annual flow of the river at Kerr Dam is approximately 7,800 cfs or about 1 cfs per square mile of drainage area.

Reservoir Projects. Six projects are in operation in the Roanoke River Basin, two Corps multiple-purpose projects and four private power company projects, as shown on figure 2. The Corps projects, John H. Kerr and Philpott, were authorized for flood control and power, but recreation has become a very significant purpose for both. Gaston and Roanoke Rapids are hydropower projects with Gaston having 3 feet of flood storage to replace valley storage eliminated by the two reservoirs and with Roanoke Rapids having responsibility for maintaining minimum flows in the Lower Roanoke River. The Smith Mountain Combination Project (Smith Mountain and Leesville) is a run-of-river pumped storage project. Smith Mountain has flood storage by virtue of limited-length spillways. Sections through the dams are shown in figures 3 through 8.

WATER QUALITY CONTROL

Problems. Investigations of water quality in the Lower Roanoke were made just prior to the construction of Kerr Dam. Dissolved oxygen was near 90% of saturation at the lowest point. Soon after Kerr project was completed the D.O. was found to be as low as 38% of saturation at the lowest point. Low flow releases from Kerr were sufficient to maintain good quality water under conditions which existed prior to construction, but while Kerr was

[1]Chief, Reservoir Control Center, Wilmington District

being built, industry was expanding. Although releases from Kerr were at times devoid of dissolved oxygen, recovery was very rapid in the open channel below the dam. By the time the released water reached the pollution source, it was more than 90% saturated. However, the industrial and municipal pollution load added to the river at Roanoke Rapids was sufficient to reduce the dissolved oxygen to below 40% of saturation at the low point on the sag curve.

In 1955 the Roanoke Rapids project was placed in operation, assuming responsibility for low-flow releases previously made from Kerr project. Although the low-flow release rate was not changed, the Roanoke Rapids project caused an average of 2.5 ppm reduction in the D.O. content of the water downstream. Frequently during the summer, the D.O. content of the water would drop well below the level required to sustain fishlife.

At this time, the Federal Power Commission was considering an application by Virginia Electric and Power Company for a license to build and operate Gaston project. The effects that the Roanoke Rapids project had on downstream water quality raised serious questions regarding the potential effects of another reservoir on water quality. These questions caused State agencies, concerned with maintenance of water quality and preservation of fish and wildlife, and industrial interests, dependent on the river for disposal of wastes, to intervene before the Federal Power Commission against the license for Gaston. Their purpose was to delay issuance of the license until the probable effects of another impoundment could be fully investigated.

Dissolved Oxygen in Reservoir Releases. To insure the release of water with a high dissolved oxygen content from Gaston Reservoir, Virginia Electric and Power Company proposed to construct a submerged weir around the turbine intakes. The submerged weir would form an underwater barrier causing water passing through the turbines to come from the upper layer of the reservoir. Since the use of a submerged weir to act as a high-level intake was new, many were skeptical of its effectiveness. In order to test the effectiveness of the submerged weir, Virginia Electric and Power Company constructed one around the intakes of their existing Roanoke Rapids Dam. The weir, constructed of crushed stone, extends upward to within 25 feet of the surface and in effect is an integral part of the intake system.

A comprehensive test of the Roanoke Rapids weir was planned by State and Federal agencies, industry, and Virginia Electric and Power Company and carried out during late summer and early fall of 1957. This was one of the most intensive limnological studies ever performed. Up to 24 engineers, chemists, biologists, limnologists, and samplers were in the field at times. Approximately 15,000 separate chemical and physical measurements of water quality were made.

In order to understand the performance of the submerged weir in Roanoke Rapids Reservoir, it was necessary to understand the effects of upstream factors. Therefore, the study program included the collection

and analysis of samples at stations located to determine the quality of Kerr Reservoir discharge, reaeration over the reach of river bed between Kerr Dam and Roanoke Rapids Reservoir, dissolved oxygen and temperature patterns and water movement in Roanoke Rapids Reservoir, the quality of water in the Roanoke Rapids discharge, and the quality of water downstream.

The hydraulic performance of the submerged weir was a subject of considerable study. This work, conducted by Dr. D. W. Pritchard and J. H. Carpenter of the Chesapeake Bay Oceanographic Institute, included measurements of the water movement in the vicinity of the weir and lower reservoir. Four methods of direct measurement were employed: (1) Gurley Current Meter, (2) confined drags, (3) free-drifting drogues, and (4) fluorescent dye tracer.

Data from all four techniques of observing the pattern of water movement were combined and velocity-versus-depth curves for various locations and discharge rates were determined. On the basis of these curves, the percentage contribution from each 5-foot layer to the discharge was determined. Table 1 shows the percent contribution of each 5-foot layer of the reservoir 500 yards upstream from the weir at the discharge rates shown.

TABLE 1

PERCENT OF DISCHARGE CONTRIBUTED BY EACH 5-FOOT LAYER IN ROANOKE RAPIDS RESERVOIR

	Discharge rate, cfs		
Depth interval, ft.	2,000	6,000	12,000
0-5	0.0	5.0	9.4
5-10	0.0	14.8	21.0
10-15	7.5	23.8	21.3
15-20	32.8	23.8	18.0
20-25	34.3	17.4	13.9
25-30	17.9	9.9	9.4
30-35	6.0	4.2	4.6
35-40	1.5	1.0	1.7
40-45	0.0	0.0	0.7

These data show (1) only a small percent of the flow originates at depths below 35 feet; (2) the layer from which the maximum contribution to the flow

originates increases in depth with decreasing flow, for 12,000 cfs it is centered at 10 feet, for 6,000 cfs it is centered at 15 feet, and for 2,000 cfs it is centered at 20 feet; and (3) there is no significant change in percent contribution with flow for the layers below 35 feet, but there is a marked increase in percent contribution for the upper 5 feet with increasing flow.

The final check on the efficiency of the submerged weir in the Roanoke Rapids Reservoir is provided by the data collected below the impoundment at the bridge crossing Roanoke River at Highway 48 bridge. During the survey period, this station was sampled a total of 1092 times, usually for dissolved oxygen, temperature, and turbidity. The results for temperature and dissolved oxygen are summarized in table 2.

TABLE 2

SUMMARY OF DISSOLVED OXYGEN AND TEMPERATURE SAMPLES AT HIGHWAY 48 BRIDGE

	Dissolved oxygen, mg/l	Temperature, °F
Maximum	8.6	84.2
Arithmetic average	6.3	76.2
Minimum	2.7	71.0
Number of samples	1092	1082

These data show water of relatively good average quality, but with a wide range of values separating the maximums and minimums, especially with respect to dissolved oxygen.

An analysis of the data shows that the dissolved oxygen content of the waters selected by the weir for discharge from the reservoir is closely related to the rate of discharge from the reservoir. At low discharge rates, the dissolved oxygen in the discharge is less, other contributing factors being equal, than for high discharge rates. This is in keeping with the velocity-versus-depth curves. Under conditions of minimum discharge at Roanoke Rapids Dam (2000 cfs), water is selected from a narrow range of elevations (centers at 20 feet below surface) immediately above the weir crest, with little mixing with the surface layers. The quality of water at this elevation is influenced by several factors, including the rate of discharge from Kerr Dam for the preceding several days, the rate of wind

mixing and reaeration in Roanoke Rapids Reservoir in the preceding several days, the rate of discharge from Roanoke Rapids Dam for several preceding days, and the degree of thermal stratification above the weir-crest elevation at the time of discharge. The minimum dissolved oxygen values observed at Highway 48 bridge represented the worst combination of these factors.

How can the very low dissolved oxygen readings be explained?

Water entering the headwaters of Roanoke Rapids Reservoir varies considerably in quality. Compared to the surface water in the reservoir, the inflow water is relatively cool, especially during periods following heavy discharges from Kerr Reservoir. In the extreme upper reaches of the reservoir, high velocities and the resulting turbulence prevent stratification. Eventually, the inflow reaches wider and deeper sections of the reservoir of such cross-sectional area that turbulence is no longer sufficient to prevent stratification between the cool inflow and the warmer surface waters in the reservoir. The cool water then sinks beneath the surface and becomes a density underflow.

The inflow continues down as a density underflow until it reaches its own density level, which varies in elevation, depending on the temperature of the reservoir as well as the thermal structure within the reservoir. Joining its density layer, the new inflow becomes the tail end of that layer. The hydrostatic head of the extreme upstream end of the inflow, which is at a higher elevation, tends to compress and thicken the downstream portion, displacing the warmer waters above upward.

The volume of water that can be discharged from Kerr Reservoir in a single peaking-power period is large compared to the volume of Roanoke Rapids Reservoir; therefore, the vertical displacement of warmer water immediately above the stratum corresponding to a cool inflow is considerable. Water thus displaced upward may be low in dissolved oxygen, since it may have been stored at the intermediate depth for a considerable time with little chance for reaeration. When water with such low dissolved oxygen is raised to the elevation of the weir crest or above, it may be withdrawn alone or mixed with other water from above and below, depending primarily on the Roanoke Rapids discharge rate. This fact accounts for the occasional observed periods of relatively low dissolved oxygen in the Roanoke Rapids Reservoir discharge.

As another measure of the effectiveness of the submerged weir in selecting water of relatively good quality from the impoundment, the data obtained at Highway 48 bridge during the study can be compared with data collected prior to the installation of the weir. Available data are summarized in table 3.

TABLE 3

COMPARISON OF ROANOKE RIVER WATER QUALITY AT HIGHWAY 48 BRIDGE FOR 1953, 1956, AND 1957

	Dissolved oxygen, mg/l			Temperature, °F		
	1953	1956	1957	1953	1956	1957
Maximum	9.0	6.5	8.6	84.2	77.0	84.2
Upper quartile	8.2	6.0	6.9	78.8	75.2	77.8
Arithmetic average	7.9	5.4	6.3	77.9	73.4	76.2
Median	7.9	5.6	6.3	78.8	73.4	76.1
Lower quartile	7.5	4.7	5.7	77.0	71.6	74.3
Minimum	7.0	3.2	2.7	73.4	71.6	71.0
Number of samples	47	21	1092	45	21	1082

Comparison of the dissolved oxygen data shows all 1957 dissolved oxygen values except the minimum are significantly higher than the corresponding 1956 values, but lower than the 1953 values. These data show a significant improvement in dissolved oxygen concentration below the Roanoke Rapids Dam over the post-dam but pre-weir period. The improvement can be attributed to the submerged weir surrounding the turbine intakes and providing the equivalent of a high-level intake. The survey resulted in the following conclusions:

1. The submerged weir in Roanoke Rapids Reservoir is hydraulically effective in selecting, for discharge from the reservoir, water primarily from the layers above the crest of the weir.

2. The weir causes a significant improvement in average water quality. Because of the relatively small storage capacity of the Roanoke Rapids Reservoir compared to the large releases from Kerr Dam, however, such releases cause occasional displacement of low-quality water from intermediate levels upward into the layers above the level of the weir. The water thus displaced upward then becomes available for withdrawal over the weir. Water thus selected may at times be of undesirably low dissolved oxygen content.

3. The submerged weir has effectively solved the problem of water quality at high flows below Roanoke Rapids Dam.

4. Based on observations in Roanoke Rapids Reservoir, the weir in the proposed Gaston Reservoir should be redesigned to extend upward to within 15 feet of the surface, instead of 25 feet as originally planned.

Upon completion of the study, consideration was given provisions that might be included in the Gaston Project license relating to minimum flows and minimum water quality. Provisions acceptable to the Virginia Electric and Power Company and the agencies concerned were finally agreed upon. Upon reviewing the Gaston Project, the Federal Power Commission concluded that "the proposed Gaston development and the constructed Roanoke Rapids development shall be considered as units of one complete project." The license for the Roanoke Rapids Project was amended to include Gaston Dam with a submerged weir. This license is unique in that it not only established a schedule of minimum flows to be maintained downstream from Roanoke Rapids Dam, it also specified minimum water quality in terms of minimum pounds of dissolved oxygen to be discharged per day.

Filling of Gaston Reservoir was completed in December 1962. Since that time the power company has never failed to meet the license requirement for releasing 78,000 pounds of dissolved oxygen per day. However, the submerged weirs have been only 99.99 percent successful. There are times of both minimum flow periods and high flow periods when the dissolved oxygen drops below 6.0 mg/l. When this occurs during low-flow periods, the minimum flow is passed through two turbines instead of one. With low loads on each turbine the vacuum breakers on the units admit air which is absorbed by the water passing through the turbines. During high flow periods a quantity of high dissolved oxygen water is spilled from near the surface of the reservoir. This, when mixed with the turbine discharge, brings the dissolved oxygen content of the total flow up to the desired level.

Another way of expressing the quality of a water is in the waste assimilative capacity. Table 4 gives the assimilative capacity of the lower Roanoke River at various stages of development in terms of pounds of 5-day, 20°C. BOD.

TABLE 4

WASTE ASSIMILATIVE CAPACITY IN
TERMS OF POUNDS OF 5-DAY, 20°C. BOD

Natural flow (925 cfs) prior to 1952 (Min. 7-day mean flow occurring 1 yr. in 10)	51,000
Post-Kerr Dam (2,000 cfs) 1952-1955	109,000
Post-Roanoke Rapids Dam (2,000 cfs)	
Without Weir 1955-1956	80,000
With Weir 1957-1962	93,000
Post-Gaston Dam (2,000 cfs) 1963-Present	109,000

Pollution Load. By far the greatest pollution load added to the Roanoke River occurs at Roanoke Rapids, N.C. A major portion of this load comes from one large industry. A review of the history of pollution from this single source will give a good picture of the critical pollution load in the river. I have previously stated that while Kerr Dam was being constructed, industry was expanding. In 1942 a paper company added a pollution load of 10,000 pounds of BOD. By 1953 this had increased to 90,000 pounds.

While the company continued to expand, it began installing waste recovery equipment and making operational changes to reduce the pollution load dumped into the river. In 1953 the plant discharged into the river 272 pounds of BOD for each ton of pulp processed. By 1955 this figure had been reduced to 127 pounds and by 1956 to 117 pounds.

Although this paper company still discharges the largest single pollution load into the Roanoke River they have greatly reduced their total pollution load at the same time they were expanding their plant. Their efforts are continuing and they hope to soon meet the state requirement of secondary treatment or equally effective treatment and control.

Summary. In the 1940's and early 1950's a deplorable situation developed on the Lower Roanoke River. Numerous interests were exploiting the river for their own gain with no consideration given to the rights or needs of others. New industries were coming into the valley and old ones were expanding. Extensive fish kills became common. Odors, foam covers, water discolorations and luxuriant growths of bacterial slime were in evidence in certain reaches of the river. All interests were quick to justify their own activities on the river and to point an accusing finger at all other interests.

Finally a "Steering Committee for Roanoke River Studies" was organized with representatives from State and Federal agencies, private industries and the general public. At times this committee appeared to be doomed to failure but finally they convinced all interests that there would have to be give and take and above all be willing to talk and negotiate differences even when at first sight it appeared that there was no common ground for reaching solutions. Task forces were formed, study programs were assigned, and everyone went to work. Out of this chaotic situation has emerged a reach of river fully developed for hydropower supporting a greatly expanded industrial complex with capacity to support additional industry while easily meeting the state standards for water quality.

Remaining Problems. One major problem remains unsolved. That is the quality of water released from Kerr Reservoir. While submerged weirs have worked well downstream, they would not be satisfactory at Kerr because of reservoir level fluctuations and large storage. Other methods of improving the outflow from Kerr must be found.

FISH PRESERVATION AND ENHANCEMENT

Basin Fishery. Excellent fishing exists in many areas of the basin today as a result of reservoir developments. Notably are bass, crappie and trout fishing in Philpott and Smith Mountain Reservoirs; trout fishing below Philpott Dam; bass and crappie in Leesville, Kerr, Gaston and Roanoke Rapids; striped bass in Kerr and Gaston and in the rivers above Kerr. The striped bass fishery in the lower Roanoke appears well on the road to recovery from near destruction. To what degree the reservoir projects contributed to their near destruction may be subject to question but I would like to trace the development of our present plan of operation from the beginning.

Operation of Kerr Reservoir for Striped Bass. The lower Roanoke River has historically served as a spawning and nursery area for a large population of migratory fishes including shad, alewife, striped bass, white perch and, to a lesser degree, menhaden. While others exist in greater numbers, by far the most glamorous and the most eagerly sought after by both sport and commercial fishermen is the striped bass.

Because of its unique spawning habits, it was recognized from the planning stage of Kerr project that regulation of the river by reservoir projects could have an adverse effect on the striped bass. Meeting the needs of the striped bass has always been a high priority item in planning project operations.

At the time Kerr went into operation, it was believed that a small flood of at least three days duration was necessary to attract the fish up the river to the spawning grounds from Albemarle Sound. So the plan was to produce a flood by releases from storage, if one did not occur naturally. Initially it was felt that a 2,000 cfs minimum release from Kerr during the spawning season was adequate. The first year of operation proved this to be incorrect. Since that time numerous studies have been made and varying amounts and timing of flows have been tried.

The Steering Committee for Roanoke River Studies recommended instantaneous river discharges not less than 2,000 cfs between 1 and 25 April; not less than 5,550 cfs between 26 April and 4 May; not less than 8,950 cfs between 5 and 20 May; and not less than 5,550 cfs between 21 May and 15 June. The 2,000 cfs flow was made a minimum flow requirement of the license for Gaston-Roanoke Rapids. The Corps agreed to raise the rule curve at Kerr 2 feet in order to store additional water to be released to supplement natural flows during the spawning season. The 2 feet would be filled with inflow above that required for minimum power requirements. It was realized that inflows were sufficient to fill this 2 feet in only 9 of every 10 years. This was acceptable to all interests since providing more would have a serious effect on other purposes which the project must serve. The Kerr rule curve is shown on figure 9.

This plan has been very satisfactory even though river flows were well below normal for several years. Since the pollution load on the river has

been reduced, we have been able to discontinue the 8,950 cfs rate for 5 to 15 May and use the water saved thereby to extend the period of 5,550 cfs flow.

Studies of the striped bass are continuing but indications to date are that they have made a remarkable comeback since the pollution load in the river has been reduced and the increased flows during the spawning season have been provided.

RECREATION

Recreational Use. When Kerr Dam was constructed, there was little interest in use of the reservoir for recreation. Today 3.5 million people visit Kerr and Philpott annually. The visitation numbers at the other projects are not available but they have far exceeded all earlier predictions.

Kerr and Philpott Reservoirs are used primarily by short-period visitors, and shore facilities have been developed for camping, picnicking, boat launching, etc. By far the greatest recreational use made of the other reservoirs is private cottages or homes along the shoreline. Fisherman use all of the reservoirs. Ample boat launching ramps have been provided at all reservoirs to permit easy and convenient access to the water by boaters.

Problems. The one big problem insofar as recreation is concerned is water level fluctuations. Leesville Reservoir has a planned weekly fluctuation of 10 feet and a maximum fluctuation of 13 feet. Yet this is the only reservoir in the basin on which there has been no complaint. Shoreline development and recreational use of Leesville is keeping pace with the other reservoirs.

Although recreation was not one of the purposes for which Kerr and Philpott projects were authorized, it has always received a high priority in the actual plan of operation of the projects. The rule curves provide for a full level pool during the recreation season. Only in extreme low-flow periods do power commitments require a substantial drawdown during the recreation season. Even so, when Kerr Reservoir was drawn down to 5 feet below the rule curve in August 1967 and 7 feet below in August 1968, recreational interests got together to form the "Kerr Reservoir Protective Association" to promote maintenance of a level pool at Kerr. Water conditions were much improved in 1969, so there was no reason for action by the Association, but they are well organized and ready to object to any operation that would cause conditions to be less than ideal for recreation.

Another problem at Kerr, which probably did much to bring on the complaints about water levels, is that the boat launching ramps do not extend into the reservoir to a sufficient depth. All ramps were constructed after the reservoir was filled. The lower end of 18 of the 27 ramps are exposed by the planned annual drawdown. None of the ramps extend to the recommended depth.

Ramps are being extended whenever water levels and work load will permit. The lesson to be learned from this problem is to build boat ramps before the reservoir is filled.

SUMMARY

Although the six reservoir projects were justified and constructed as power-only or flood control and power projects, they are, nevertheless, providing millions of dollars each year in other benefits. With a reliable count of 3.5 million visitors to two projects each year, a claim of over 6 million visitors to the six projects would appear very conservative. The waste assimulative capacity of the lower Roanoke River has been doubled. Low flows on the Smith, Dan, and Staunton Rivers have been substantially increased. Excellent fishing is available throughout the basin. While many problems have been faced on the process of developing a plan of operation for these projects, most have been settled with but little compromise on the part of any interest.

SUMMARY OF DISCUSSION

Compiled by H. O. Reese[1]

The encroachment on flood control storage that results from the rule curve adopted for Kerr Reservoir to provide supplemental flows during the spawning season of the striped bass (spring months of March through June) was discussed. It was explained that results of operational studies based on period-of-record recorded flows indicated that the encroachment on flood control storage at this time of year would not adversely reduce the flood control benefits that are obtainable from project operation. The major single floods requiring large amounts of flood control storage have generally occurred during the late summer early fall months and are associated with tropical hurricane storms.

The question was raised as to why the practice of dividing low power loads between two turbines to admit air through the vacuum breakers in order to increase the level of dissolved oxygen in turbine discharge was not adopted as a full time operation technique. It was explained that the practice resulted in a loss of efficiency in power production and also that cavitation may occur. It was noted that the lower the dissolved oxygen content of the water, the more effective is this process of increasing the dissolved oxygen level by admitting air to the turbines.

In response to questioning, the participants were assured that power revenue benefits were not optimized at the expense of the overall total project benefits that are obtainable from the consideration of all project purposes.

[1]Chief, Special Assistance Branch, The Hydrologic Engineering Center

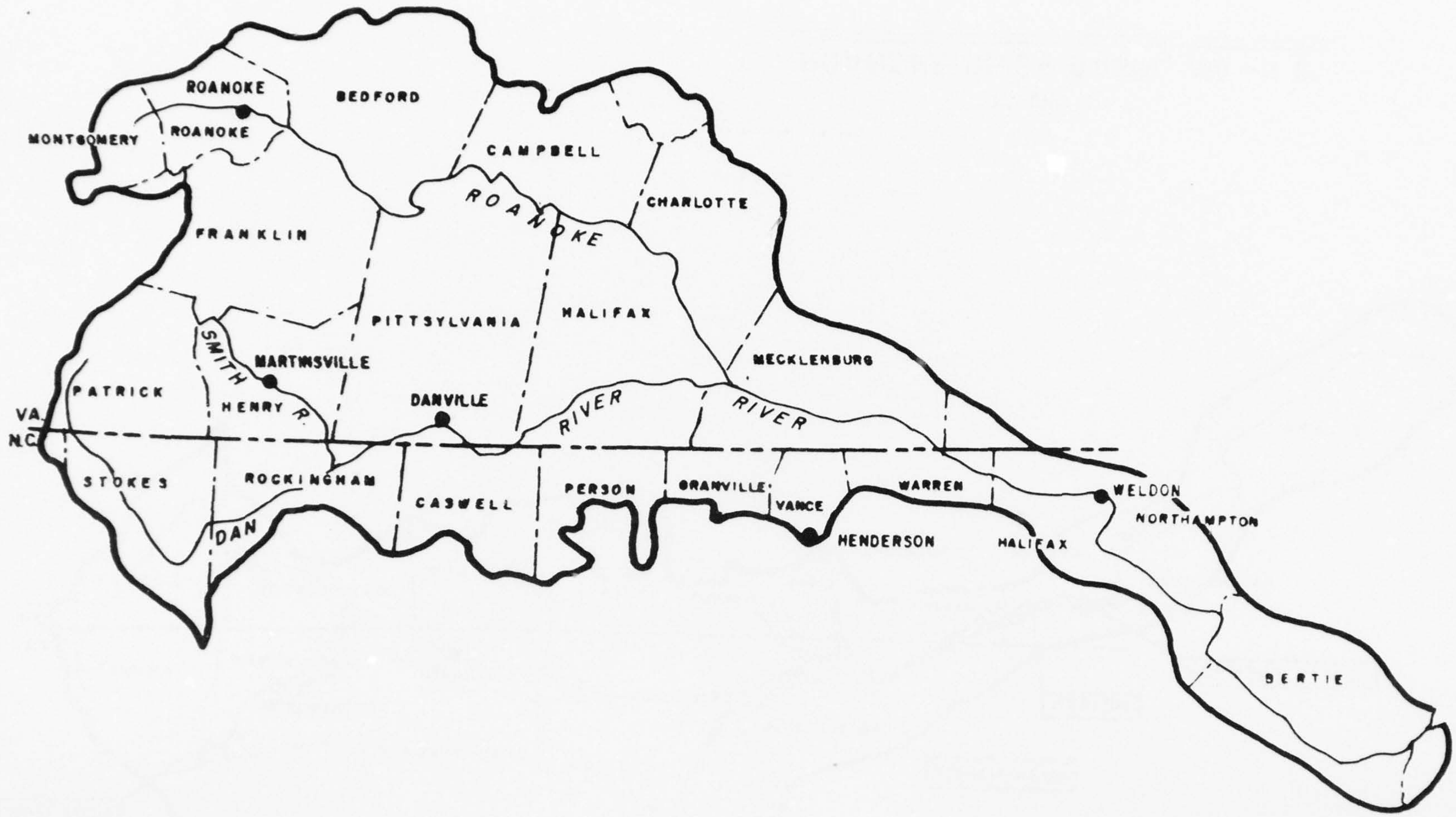

FIGURE 1

ROANOKE RIVER BASIN, VA.-N.C.

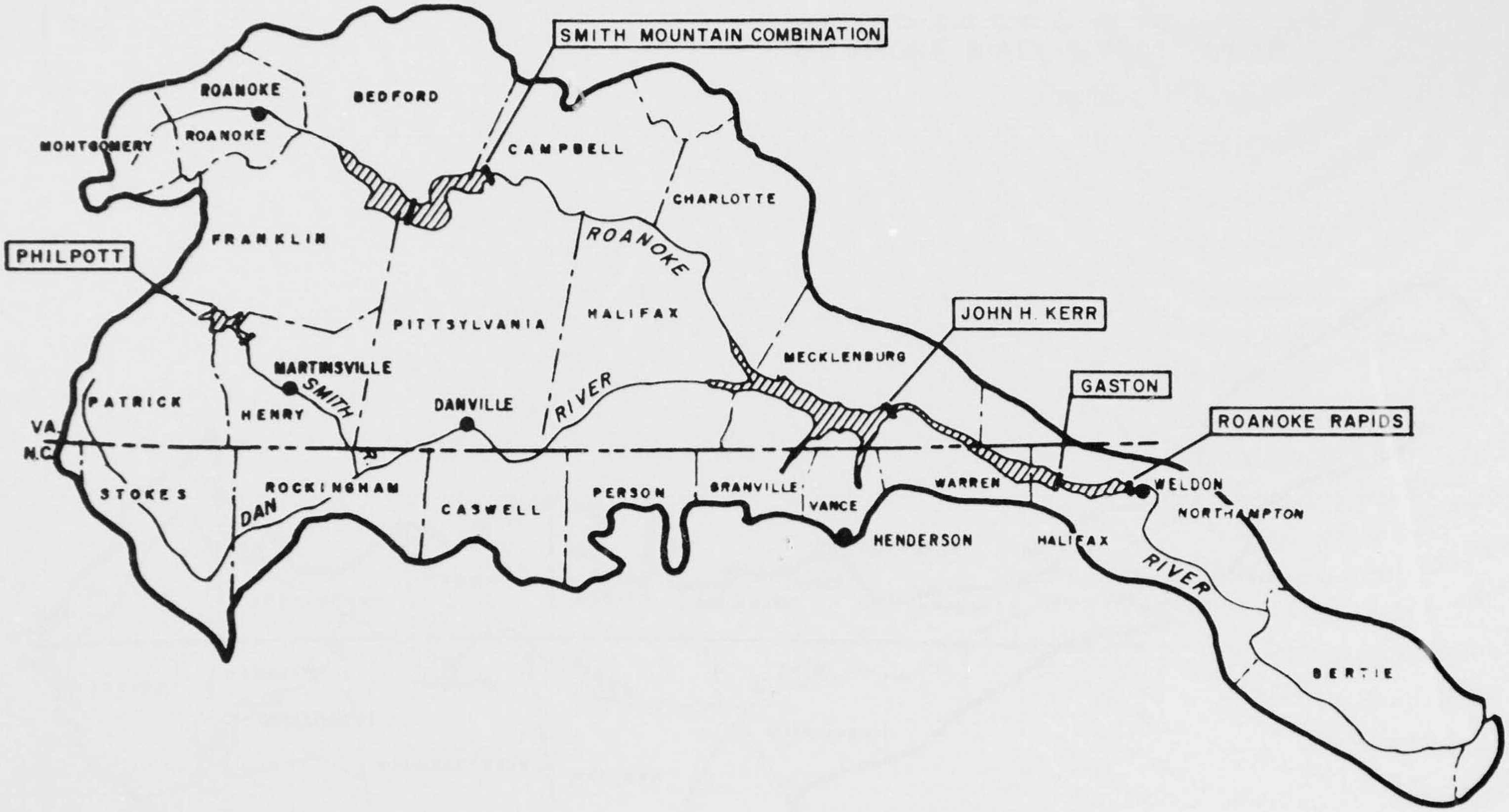

FIGURE 2

ROANOKE RIVER BASIN, VA.-N.C

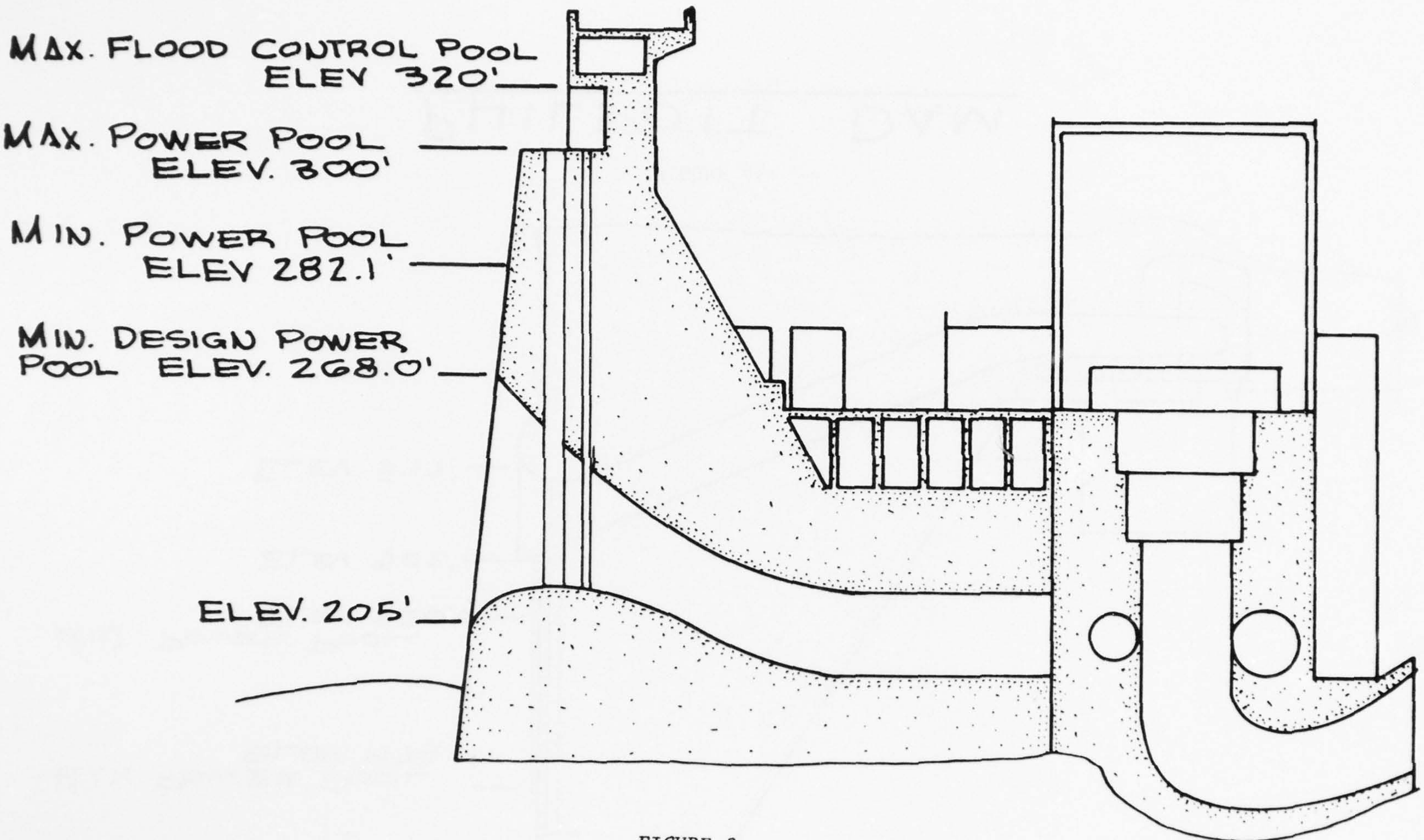

FIGURE 3

KERR DAM

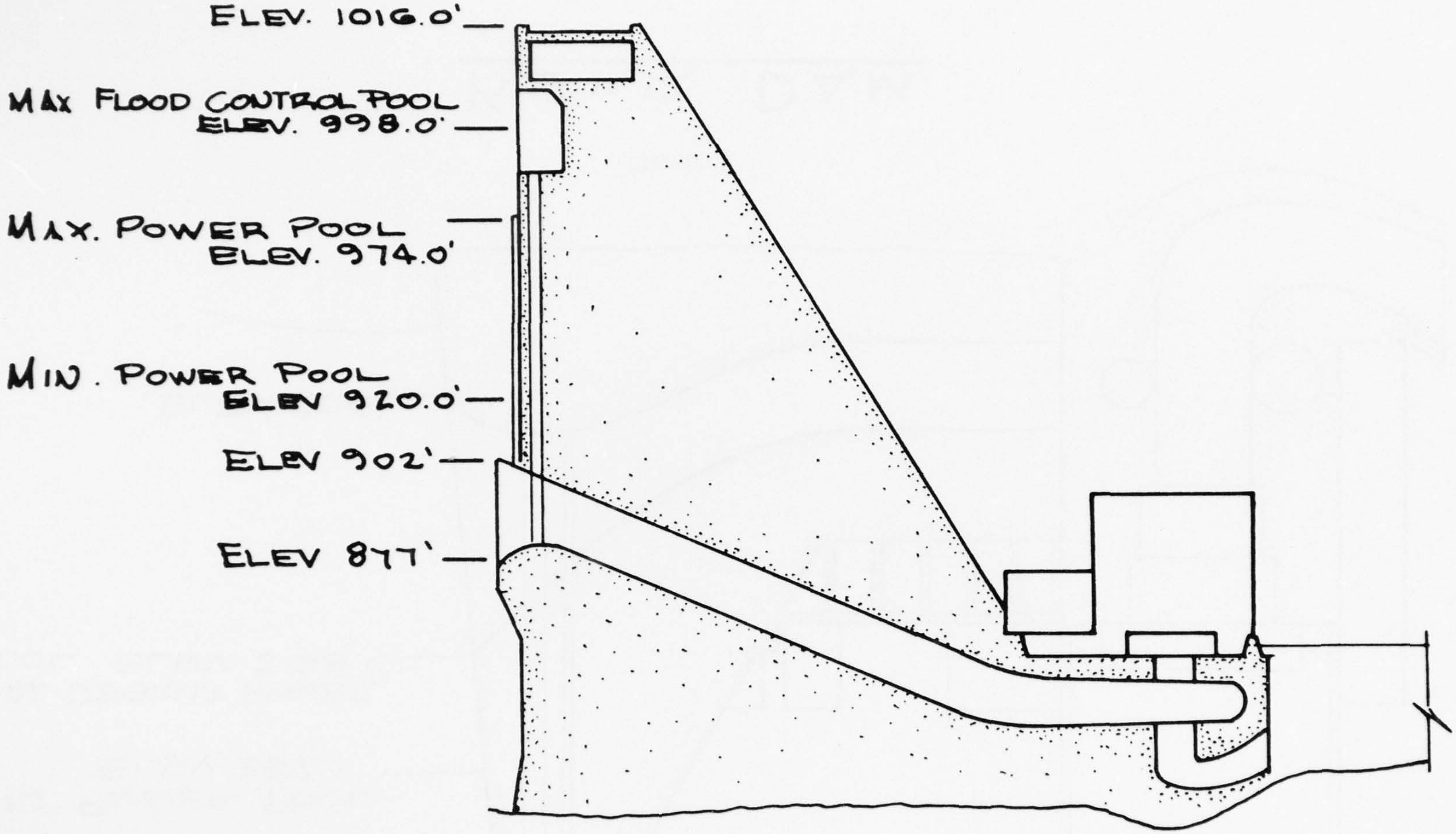

FIGURE 4

PHILPOTT DAM

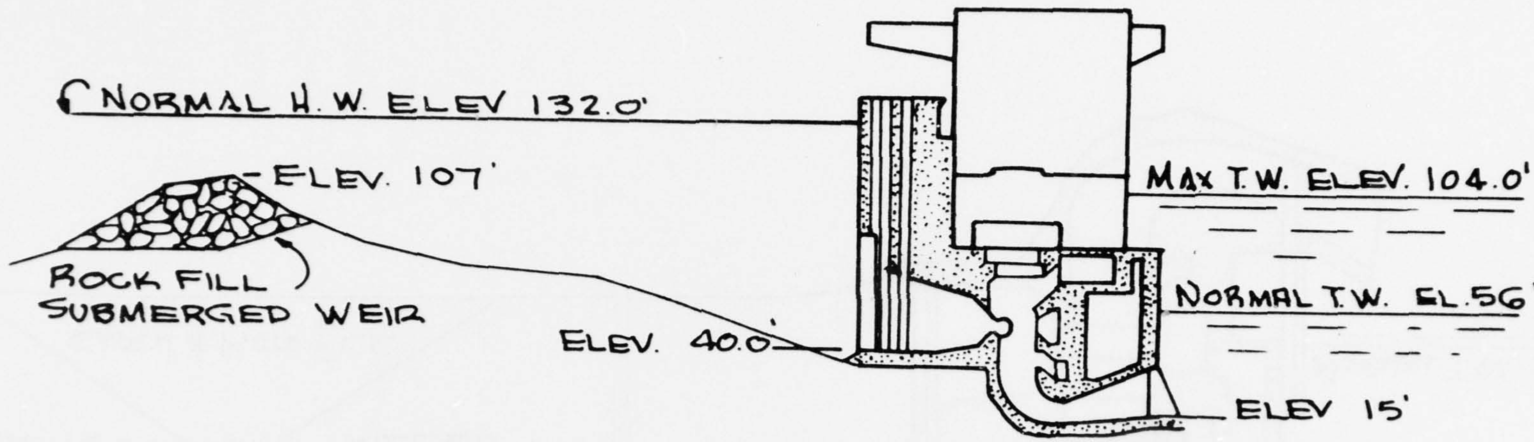

FIGURE 5

ROANOKE RAPIDS DAM

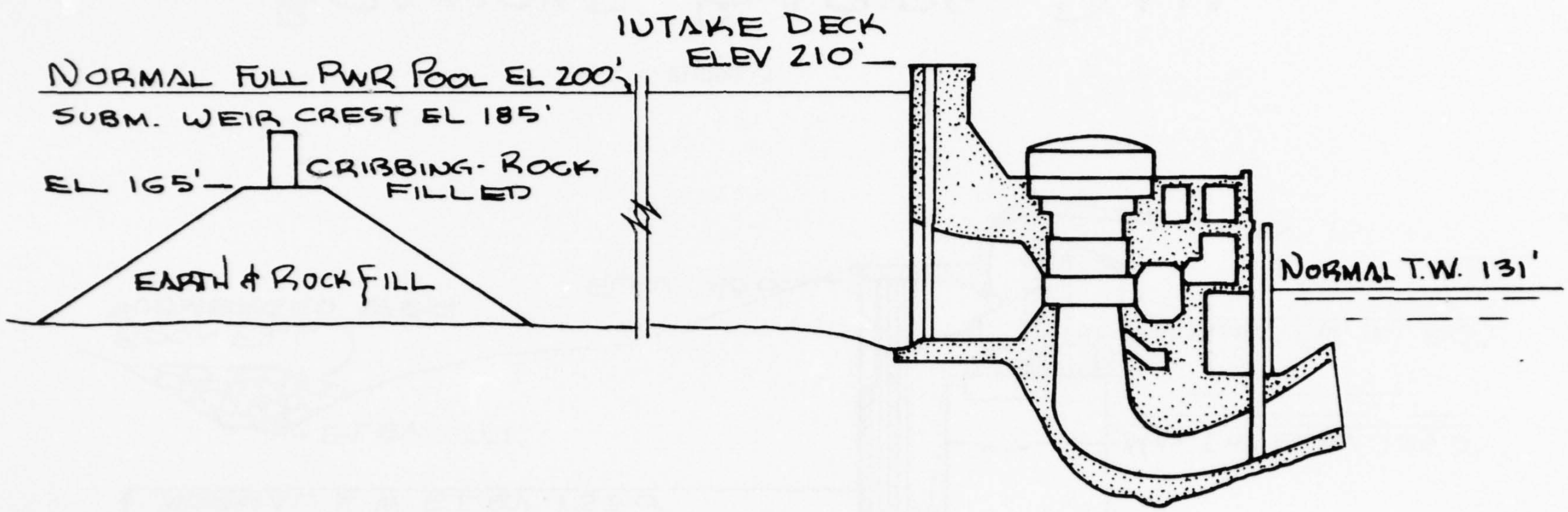

FIGURE 6

GASTON DAM

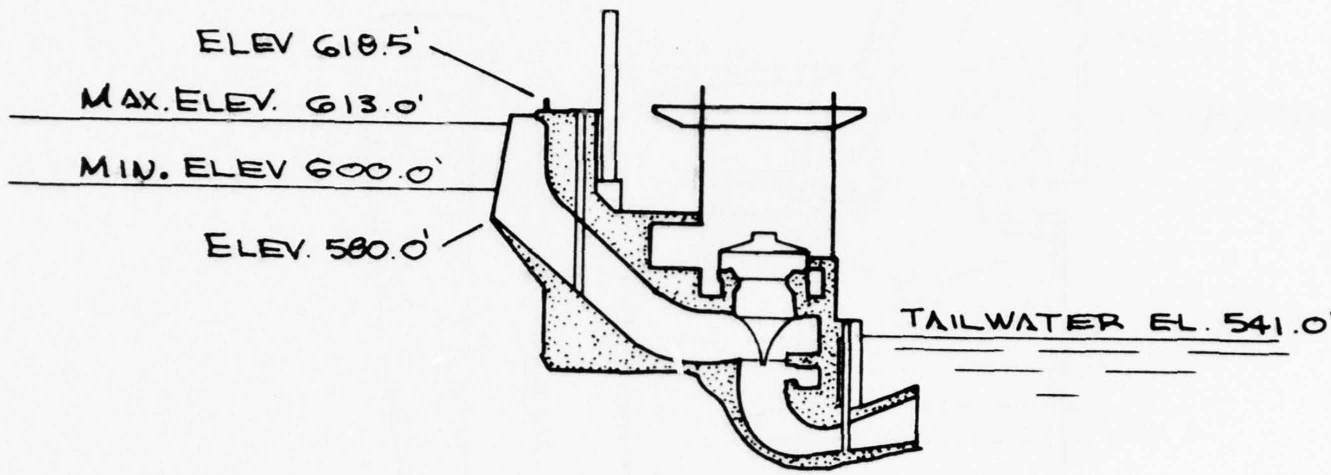

FIGURE 7

LEESVILLE DAM

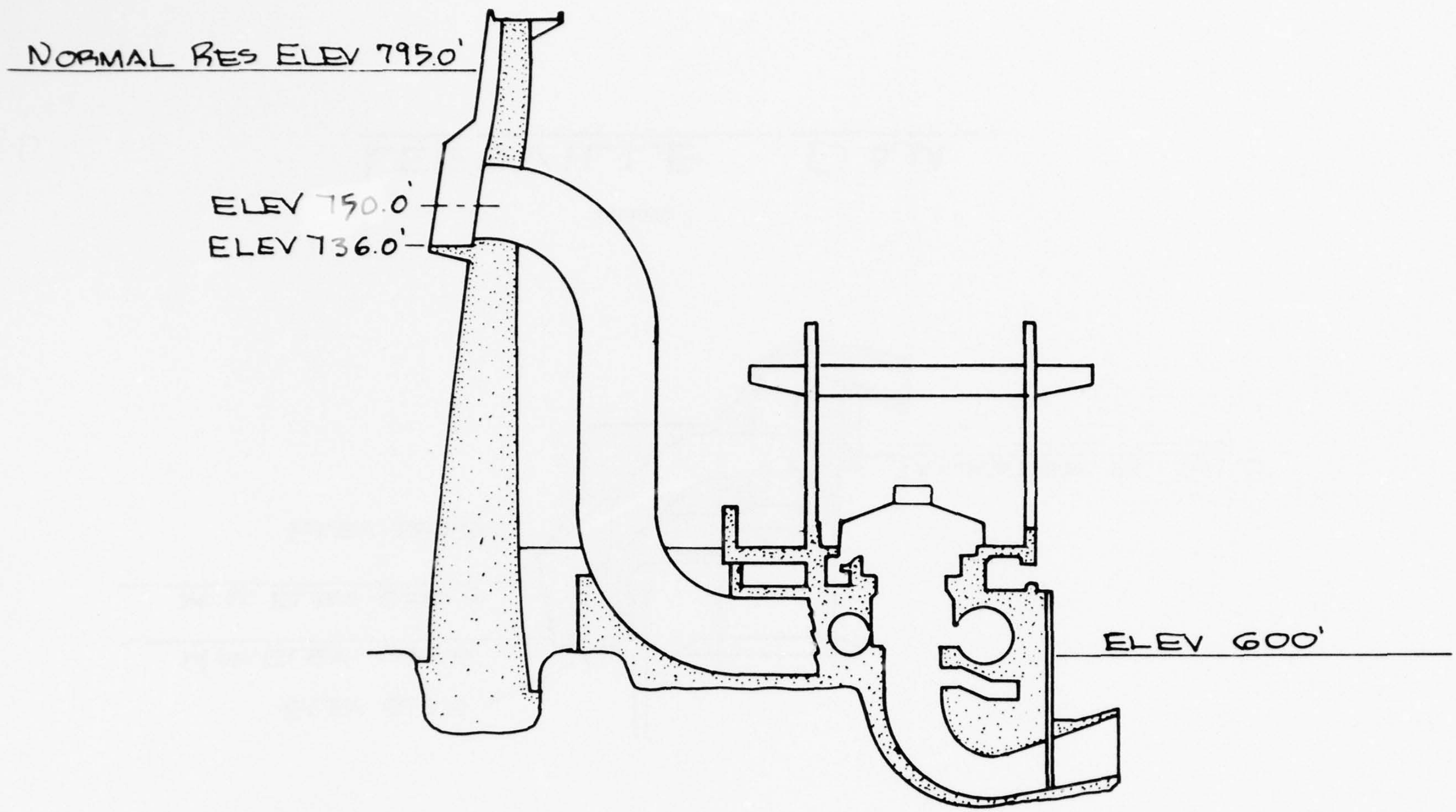

FIGURE 8

SMITH MOUNTAIN DAM

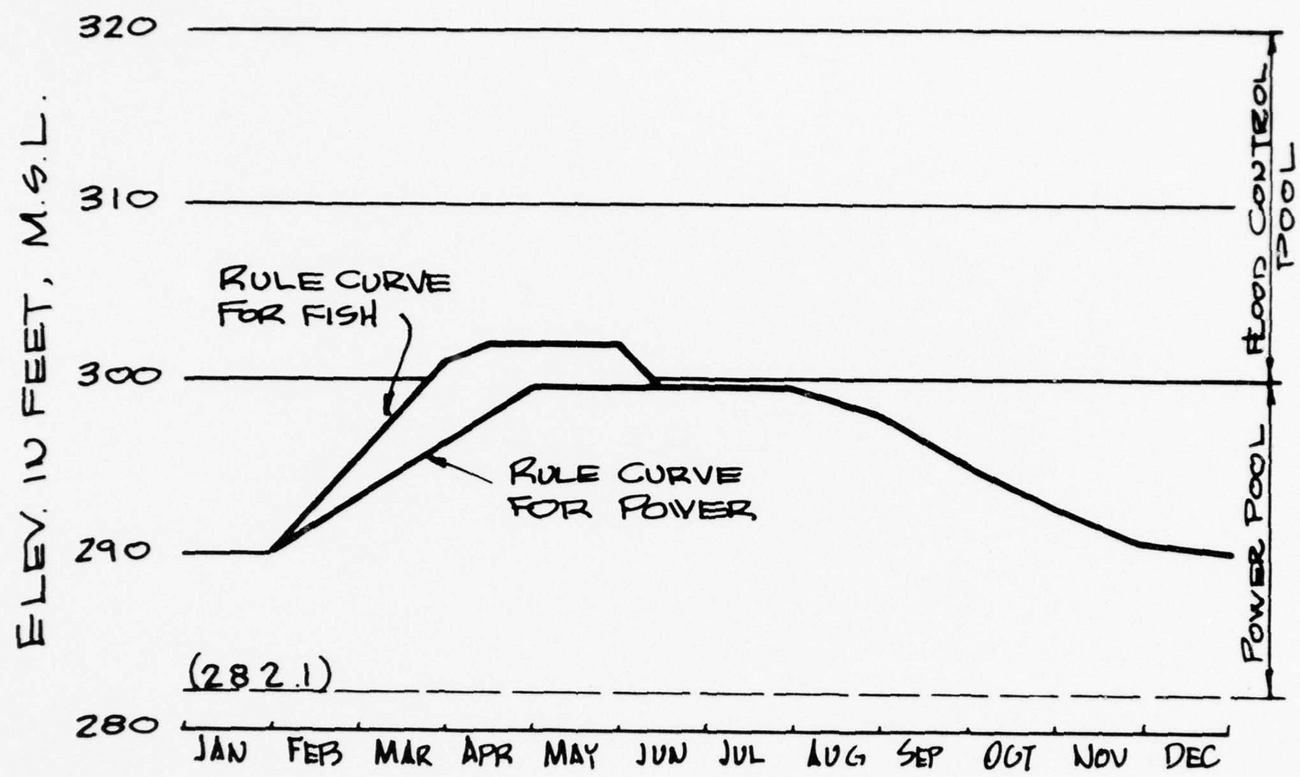

FIGURE 9

KERR RULE CURVE

COMPARISON OF PRE-CONSTRUCTION AND
POST-CONSTRUCTION RESERVOIR REGULATIONS

By

Warren L. Sharp[1]

INTRODUCTION

A comparison of reservoir regulation procedures applied during the planning and design phase with regulation techniques applied during actual operation, ranges from no discernible difference to little similarity between the two plans. After a reservoir project is constructed, operation regulations must be changed from time to time because of one or more of three factors:

a. Needs for reservoir services change

b. Controlling conditions change

c. Technology changes

Because of the extreme complexity of problems associated with reservoir operation and the temptation to change operating rules during emergencies without adequate study, it is necessary for the regulations to be specific and firm. However, they can and should be flexible enough to accommodate the influence of changing hydrologic and meteorological conditions. Few completed projects can claim immunity to the influences mentioned above, but there are certain reservoirs that are less susceptible to change than others. Characteristics of projects and conditions commonly associated with minimal or no change in operating procedures after project completion are those where: (1) reservoir outflows are essentially uncontrolled, (2) reservoir inflow and uncontrolled streamflow prediction, if required, are simple tasks, (3) all other techniques involved are free of complexities because the number of project purposes and constraints are few and (4) all conditions relating to operational objectives have remained unchanged since project formulation. Any one or all of these conditions may apply to the same project.

This paper discusses the reasons for changing regulations and summarizes briefly the results of a sample survey of regulation changes that have taken place over the past few years. In order to be more meaningful, the discussion herein pertains primarily to projects that are at least partially controlled; i.e., projects having discharge facilities capable

[1]Assistant Chief, Reservoir Regulation Section, OCE.

of regulating releases when reservoir levels are within the conservation and flood control storage zones. Also, the discussion is directed toward all reservoirs whose operation, entirely or in part, is the responsibility of the Corps of Engineers.

CHANGES ASSOCIATED WITH STREAMFLOW PREDICTION

The first major difference experienced between pre-construction and post-construction operation plans occurs at the time of project completion, and is usually anticipated (even planned) from the early stages of design. This change concerns the degree of analysis associated with streamflow prediction, specifically with regard to: (1) the time increment used in computation and tabulation and (2) the relative quantities of hydrometerological data that are used in pre-project studies and during actual operation. These two elements are closely related; therefore, they should be coordinated during the planning and design stage, as explained later. Massive quantities of data defining the prevailing conditions are often used during actual operation, especially during flood events, to predict streamflow above and below the reservoir. This constitutes the most significant difference in pre-construction and post-construction reservoir regulation insofar as inflow prediction is concerned. Rainfall data, for example, is used on a much larger scale for a given event during real-time operation than during design and rightfully so. Similar application of data during the design phase is seldom necessary, because existing records of historical streamflow are utilized.

A few comprehensive computer programs for inflow predictions have been developed for various river basins in the nation. However, the subject has barely been touched upon insofar as development and application of new sophisticated techniques are concerned. Another development that is needed even more than a broadly applicable streamflow prediction program is an optimization procedure for selecting reservoir releases for any number of reservoirs in a system. The procedure must be suitable for both planning and real-time operation.

CHANGES ASSOCIATED WITH RELEASE CONSTRAINTS

Success or failure in achieving operational objectives of reservoirs is controlled by release selection. Therefore, all constraints and uncertainties are defined and applied in terms of their effects upon reservoir releases, which in turn is a guide to the procedures and techniques employed for achieving the objectives. Here again, as in streamflow prediction, the emphasis placed on the factors influencing releases (objectives, constraints, uncertainties, and other related parameters) often differs appreciable under pre-construction and post-construction conditions.

The time increment required in routing studies to satisfactorily determine the quantities of storage needed in reservoirs for various purposes and to formulate a plan of operation suitable for real-time application is a very important item. With regard to the plan of operation, various trial operations guided by "hindsight" analysis are performed. From these trials should evolve the best operating procedure, which in turn is applied in a "foresight" manner, not only to perform routings for final design, but to use (at least initially) in actual operation. Ideally, the time increment used to determine the foresight procedure is one that will be suitable for using massive quantities of hydro-meteorological data in actual operation. However, this compatibility may not always be feasible. When the difference between the time increment required for storage determinations during planning studies and that needed for a suitable operation is appreciable, little consideration may be given to such details of operation during the planning stage, especially when faced with impending deadlines and manpower shortages, because real-time operation is not an immediate problem.

Another significant difference between pre-construction and post-construction operation plans is the number of and degree to which constraints are considered during their development. The number of objectives, constraints and uncertainties applicable to reservoir release scheduling increases with the addition of project purposes, even though several purposes may be complementary. Several of the constraints may be given only minor attention, while others, along with uncertainties, are necessarily ignored during the planning and design stage. The decision for using a constraint when performing operational studies during project formulation is based upon the relative importance and degree of uncertainty associated with the constraint. These considerations then, control the effect that each constraint is allowed to have upon project development. Pre-construction operational studies often include only the objectives, constraints and uncertainties directly related to "authorized" project purposes. For example, forced fluctuation of the pool for mosquito contol, or curtailing releases for a few days to enhance fish spawning may be recognized as desirable, perhaps even planned as operational objectives, but are excluded from pre-construction routings insofar as their objectives and constraints are concerned; i.e., non-primary objectives are usually evaluated external of the routings, or ignored. Limitiations on the comprehensive aspects of operational studies, such as the above, should be abated in certain cases, because benefits incidental to reservoir regulation in the past, are fast becoming secondary and even primary operational objectives.

Triming the number of constraints also results from the application of familar, simplified, standard techniques, where the inclusion of more than a few constraints would either render the method too cumbersome for use or not be warranted due to the limited accuracy of the method. In addition, the use of a large time increment will render the application of certain methods and constraints impractical or even impossible.

Some of the most unreliable incidents are: (1) so-called flood control evaluations where the routing interval (time increment) is too long, (2) hydropower design based on the critical drought of record rather than on a frequency analysis, (3) master plan developments (recreation and fish and wildlife) giving little or no consideration to reservoir regulation, and (4) water supply plans involving simultaneous supplies of differing frequencies that are not solved during design.

NATURE OF REQUESTED OPERATION CHANGES

A sample consisting of 26 requests for operation change that have been made during the past few years is considered to illustrate the general nature and extent of such changes. By far the greatest number of proposals for departure from the approved reservoir regulation plans are associated with the recently increased interest in water-oriented recreation.[2] If the variations relative to the closely allied purposes of fish and wildlife are added to those of recreation, 50 percent of the cases are accounted for. The next most prominently recurring type of departure is that concerning operation for flood control and 20 percent of the cases were found to be in this category. The remaining distribution is: water quality, 10 percent; water supply, 3.3 percent; navigation, zero; hydropower, 3.3 percent; sediment, 3.3 percent; and others, 10 percent. These cases were briefly summarized by project in table 1.

The purposes of the survey were: (1) to furnish brief information about individual cases for study and future reference and (2) to obtain a categorized representation of the number and importance of cases in relation to all operational objectives recognized by the Corps. If the distribution of problems is an accurate representation of the more important reservoir regulation problems of our time, it will serve as a guide in performing hydrologic studies and developing up-to-date reservoir regulation plans.

The survey did not include cases where water supply contracts were issued for the use of storage already provided for same, nor did it include changes in regulation plans indicated only within the text of revised or updated reservoir regulation manuals. If the basic correspondence submitting and updated manual mentioned a significant change in plan, as such correspondence should, the case was included. Unfortunately, the survey did not include all of the cases involving reservoir regulation occuring after project completion. Time did not allow a survey of files within the Hydropower Branch, Planning and Operations Divisions, or even all of the hydrologic engineering files. Any lack of representation is probably limited to water supply, water quality, hydropower and navigation, however, it is felt a majority of the more important cases in all pertinent areas are included.

[2] i.e., as a primary purpose among operational objectives, Federal Water Project Recreation Act of 1965, P.L. 89-72; 79 Stat. 213-218.

TABLE 1

SURVEY OF RECENTLY PROPOSED CHANGES TO APPROVED RESERVOIR REGULATION PLANS

OPERATIONAL OBJECTIVE	CASE NUMBER	NO. OF CASES
Recreation	2, 4, 10, 13, 15, 16, 17, 19, 22, 26, 12	11
Fish and Wildlife	1, 6, 18, 16	4
Flood Control	3, 8, 11, 20, 24, 13	6
Water Quality (including low flow)	21, 22, 25	3
Water Supply (including irrigation)	25	1
Hydropower	5	1
Sediment	7	1
Navigation		0
Structural considerations	9, 14, 23	3
TOTAL		30

A brief description of each case follows:

1. Regulation for northern pike spawn. A falling pool produced by below-normal runoff and high downstream water demands would be detrimental to pike spawning. It was desired to hold the pool constant between 1 and 23 April and supply water and power needs from another reservoir.

2. Summer storage in flood control reservoirs. It was desired to establish conservation pools for esthetic values, using 3 to 5 percent of the flood control storage.

3. Reduction of target flood releases. The bank-full channel capacity was reduced from the design value of 7,000 cfs to 6,800 cfs by construction of a boat ramp. Also, seepage to flood plain begins at flow of 5,200 cfs. It was desired to reduce target release to 6,500 cfs.

4. Raise level of normal pool. Because of many shallow areas detrimental to boating, it was desired to raise the conservation pool level.

5. Temporary departure from normal operation. It was desired to change seasonal storage operations temporarily in order to perform operational studies for hydropower.

6. Permanent change in operation of water conservation area. Excessive pool fluctuation to approximately standard project flood pool level was caused by hurricane and pumped inflow. Extreme fluctuations occur almost every year. It was desired to adopt a new schedule that would not require discharge between January and June and that would call for discharges between mid-August and the end of December.

7. Creation of minimum pool. Emptying of reservoir causes discharge of large amounts of sediment, resulting in downstream control shift and streamgaging inaccuracies. It also causes accumulation of debris on trash racks. A 2,000 acre-foot minimum pool was desired, and this was estimated to trap 81 percent of the sediment.

8. Reduction in target flood control release. Target release of 12,000 cfs exceeds non-damage capacity by about 3,000 cfs. However, future power installations will require the full 12,000 cfs release. It was desired to reduce the target release to 9,500 cfs until the additional turbine is installed, and to acquire flowage easements for the full 12,000 cfs at that time.

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PROCEEDINGS OF A SEMINAR ON RESERVOIR SYSTEMS ANALYSIS, 4-6 NOV--ETC(U)

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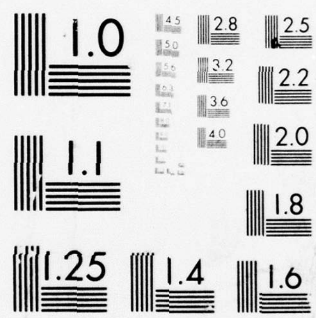


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

9. Change in the interest of dam safety. Review studies show that spillway capacity is too small. Desire authority to increase releases during severe floods, to break a rim dike during severe emergencies and to install additional flood warning facilities. These measures would be provisional, pending permanent remedial measures.

10. Special releases for recreational event. In view of the large number of requests for recreation releases, it was desired to store 2,500 acre-feet of water each year to be released for one 3-day white water canoeing event.

11. Change in flood control releases. Pending construction of an upstream reservoir, a target release of 7,000 cfs was adopted for an existing reservoir. This caused inundation of 4,200 acres of tillable land and serious protests. It was desired to institute a variable-release schedule, with releases ranging from 4,000 cfs to 7,000 cfs, depending on season and pool elevation.

12. Increase in summer pool level for recreation. Because of shallow water, only one-third of the reservoir area was suitable for boating and water skiing. It was desired to raise the pool level from 494 to 500 feet between 1 and 15 May and to draw down between 15 August and sometime in October.

13. Reduction of flood control releases. During construction of a project designed to regulate flows to 8,500 cfs, encroachment into downstream flood plains reduced the non-damage flow from 8,500 cfs to 6,500 cfs. Also, ground-water drainage is noted to occur with sustained releases exceeding 4,000 cfs. It was desired to adopt a schedule of releases ranging from 4,000 cfs to 20,000 cfs, depending on storage level and other prevailing conditions.

14. Emergency modification of operation plan. Sand boils appeared on the downstream toe of the dam during test filling. It was desired to operate reservoir to permit construction of a drainage relief system and new test filling.

15. Special release for recreation. Pool is drawn down between 15 September and 15 October with releases of about 25 cfs. It was desired to release 400 cfs for 2 days in October for slalom races.

16. Review of regulations for optimum use. In response to expressed needs for increased reservoir services, it was desired to adopt new rules, holding the reservoir low during the spring and fall flood seasons and optimum operation for flood control, fish and recreation during the summer.

17. Special operations for recreation. It was desired to use a small amount of the flood control space for special canoe-race releases during one weekend of each month from July to October. Releases would be scheduled for greatest attendance and least inconvenience to fishing.

18. Special storage for fish propagation. Satisfactory conditions for fish propagation downstream of the reservoir require 1,600 cfs during a particular season. This compares to a planned release of 1,000 cfs. It was desired to superimpose a fish and wildlife pool on the navigation pool when the inflow is substantial in order to provide a fairly high outflow.

19. Increase of recreation storage. It was desired to increase the recreation pool level 1 1/2 to 5 feet during the summer, when there is great need for additional recreation pool and less danger from floods.

20. Revision of emergency release diagram. The emergency spillway release diagram calls for releases exceeding the capacity of major urban levees before the full use of spillway surcharge storage. It was desired to revise the emergency release diagram so that releases would be held to top-of-levee capacity until the induced surcharge limit is reached, and then increase releases as necessary to protect the dam.

21. Special operation for re-aeration study. It was desired to increase the conservation pool 50 feet, thus filling 9 percent of the flood control space, in order to study re-aeration produced by turbulence in a moderately steep channel downstream.

22. Increase dependability and duration of recreation pool. It was desired to adopt a newly developed regulation procedure that would permit earlier filling in advance of the recreation season and that would extend the duration of the high pools and large lake areas.

23. Change in the interest of dam safety. Pending complete investigation of the stability of the spillway, it was desired to lower the conservation pool and to provide for larger target releases during flood periods.

24. Simplification of surcharge operation. At a particular navigation dam, the elaborate emergency release diagram is considered to be unnecessarily demanding on the operator. It was desired to substitute the simple instruction to maintain top of power pool until the full spillway capacity is reached, and then allow full releases until the pool level recedes to power pool. Studies support the adequacy of the simple operation.

25. Release of turbid water. In the event that water stored for summer conservation pool should become unsatisfactory for use as water supply, it was desired to empty the reservoir and to refill.

26. Establishment of recreation pool. It was desired to maintain the pool elevation of 1,432 feet toward the end of the snowmelt season and through the summer, insofar as possible, making minimum releases consistent with downstream requirements.

CLOSING COMMENT

As shown by the survey, there are many reasons for, and means of changing the operating plans for reservoirs to better serve the demands upon reservoir regulation. Considering the changes that inevitable take place in reservoir operation regulations after the project is constructed, there are three desired actions that should become commonplace:

1. Consider including greater flexibility in design (such as large outlet capacity, multi-level outlets, adequate easements, etc.) so that future needs can be better accommodated.

2. Recognize in planning and design reports that needs and technology are changing and that operation rules are subject to change within the limits of authority.

3. Include provision in the project documents for frequent reexamination of the operation regulations.

All views expressed herein are strictly those of the writer, and do not necessarily represent those of the Corps of Engineers. The cases speak for themselves, and even though the writer has reached further conclusions regarding the overall subject matter presented, they are being withheld in written form to allow the reader to more firmly form his own conclusions, which in turn will contribute toward a more fruitful oral discussion of the subject matter at the seminar. A few related questions worthy of oral discussion follow, with the hope that the group can find satisfactory solutions for them:

1. Are pre-project reservoir regulation studies and plans performed and developed satisfactorily in your office? Post-project studies and plans?

2. How indicative is the survey of the most significant and frequent recurring nation wide problems in reservoir regulation expected in the future?

3. Are there any areas in need of special study indicated by the survey, and if so, what are they? How do these subjects compare with

those receiving special study in your office?

4. To what extent should the Corps reduce authorized flood control storage space on a seasonal basis in existing projects for the benefit of other purposes? What restraints should be placed upon "operating for maximum net benefits", considering all operational objectives?

5. Are reservoir regulation manuals compiled in your office adequate for use under any hydrometerlogical conditions and all, except the very minor, operational objectives? To what extent <u>are</u> they used?

SUMMARY OF DISCUSSION

Compiled by E. F. Hawkins[1]

It was generally agreed that a presentation of cases where previously approved reservoir regulation plans have been changed would be valuable to all Division and District offices. Also, there are many cases where significant improvements in operation plans have been made that were within the scope of approved plans, and these would be of value to other offices.

At times, there are continuity problems caused by one branch planning and designing the project and another branch operating the project. This has caused problems since operating criteria must then be produced to agree with the design.

Some changes are due to inability to operate 100-percent efficiently, as is sometimes assumed in planning and design. This is due primarily to imperfect inflow prediction, development of the flood plain after the project is completed, and unforeseeable problems that arise from time to time.

[1] Hydraulic Engineer, Training and Methods Branch, The Hydrologic Engineering Center

RESERVOIR SYSTEMS ANALYSIS
IN THE SAN FRANCISCO DISTRICT

by

Dale R. Burnett[1]

A need for system analysis capabilities in the planning phase of river basin studies has developed within the San Francisco District during the past several years. This need has been limited to water supply yield studies. Prior to this time no great need was apparent in either the planning or operation phase of projects. The San Francisco District has been operating Coyote Dam in the Russian River basin for about 10 years. Warm Springs Dam is under construction and a third dam is authorized. These three dams, along with others in the basin which are still in the study phase, will need to be operated as a system in order to maximize benefits. The District, has prepared a computer program specifically for this operation study. One unique criterion to this operation was the variation of releases for fishery mitigation based on the maximum reservoir level reached during the prior winter. Municipal and industrial releases are made to the river in such quantity as to firm up unregulated runoff from the remainder of the basin. Diversion is made at the lower end of the river basin by means of Raney collectors and pumps. System operation to maximize the combined water supply yield from Coyote and Warm Springs dams obtained a 23 percent increase over the sum of the single reservoir yields. Operation and planning studies will be continued during the next 2 or 3 years as planners consider additional reservoirs for inclusion in the system.

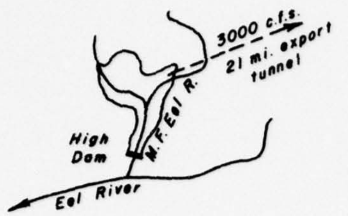
The primary need for a systems program has evolved from various basin planning studies under investigation by the San Francisco District. Many of you are familiar with the California Water Project, which has been initiated to develop water in the water-rich northern part of the State and export some of it to the water-deficient southern part of the State where 2/3 of the population resides. This plan of development, which will extend over the next several decades, will involve extensive pumping stations and tunnels for upstream delivery and transbasin diversion of surplus water. Large reservoirs which back water to the base of an upstream reservoir will offer ideal opportunities for pumped storage power developments. The development of the export water supply is based on firming unregulated runoff from Central Valley streams at the confluence of the Sacramento and San Joaquin Rivers. Surplus water and water released from storage will be diverted at this point and exported to southern California by an extensive system of canals and pumps. Ultimately, some 8 million acre-feet per year will be delivered to various points south of the Sacramento-San Joaquin Delta by Federal and State projects. Much of the analysis and project

[1]Hydraulic Engineer, San Francisco District

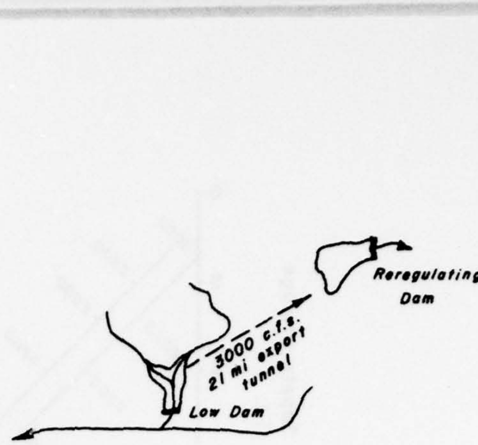
formulation studies leading to authorized projects will be done by the Corps, concurrently with other Federal and State agencies. Inclosure 1 is a map showing the location of some of the completed and potential projects. It is estimated that an average of about 900,000 acre-feet of new yield per year during a 7-year dry period similar to 1928-34 must be added to the system by 1990 in order for the State Water Project to meet existing contracts for water. The San Francisco District is finalizing a survey report on the Middle Fork Eel River with recommendation for construction of a dam and reservoir to develop this initial requirement.

The Middle Fork Eel River is a 745-square-mile tributary within the 3,600 square mile Eel River basin. Annual runoff averages about 1 million acre-feet and has ranged from extremes of 136,000 acre-feet to 2.4 million acre-feet. One proposed project consists of a 730-foot high rock-fill embankment, at the Dos Rios site, impounding a total of 7.6 million acre-feet of storage, consisting of 5.0 million acre-feet of active storage for water supply and fishery releases, 600,000 acre-feet of flood control storage and a minimum pool of 2.0 million acre-feet for potential slides, sedimentation and aesthetics. This project, in conjunction with excess flow in the Sacramento River, would be capable of increasing the annual yield of the State Water Project by an average of 900,000 acre-feet during a 7-year dry period similar to 1928-34. In addition, the project would provide 4,800 kilowatts of year-round full-capacity power from the fishery releases and provide flood control and recreation benefits. One method of conveying municipal and industrial water into the Sacramento River basin for the State Water Project could be by means of an easterly diversion through the Coast Range into Stoney Creek via a 21-mile long, 17-foot diameter tunnel. The basic plan project would inundate a unique mountain valley of about 18,000 acres, including a community of approximately 600 population. Opponents to the project feel that adequate analysis and presentation of alternative projects that would not destroy this valley were not presented. Numerous alternatives have been studied by both the Corps and Department of Water Resources. The only alternatives within the Eel River basin that are at all competitive with the basic plan require construction of more than one dam. The District has utilized The Hydrologic Engineering Center's reservoir systems program 23-53 to conduct yield studies of a number of alternative proposals. Operation studies covered the 50-year period, 1911-60. A criterion was adopted to limit the critical full-to-full period to about 15 years.

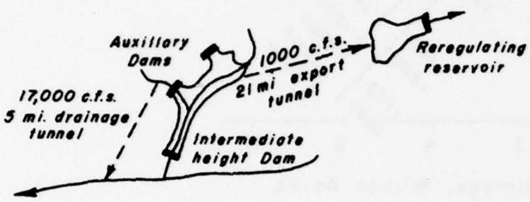
Each alternative project was sized to meet an increase in demand from the Sacramento-San Joaquin Delta of 900,000 acre-feet per year average during the 1928-34 dry period, based on a monthly diversion schedule during the 50-year routing period furnished by the State Department of Water Resources. This amounted to a 50-year average of about 350,000 acre-feet per year. Each dam was then maximized to develop all the available water from the site until either the 15-year criterion was exceeded or the physical limit of the site was reached. This required numerous trials and evaluations of computer runs using different combinations of reservoir storage, tunnel capacity, pump capacity and water supply demand. The basic plan and three alternative projects are shown schematically below:



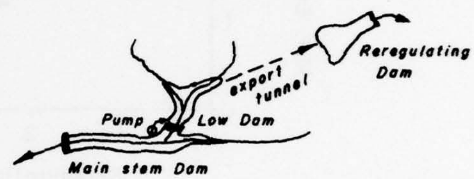
BASIC PLAN



PLAN A-1



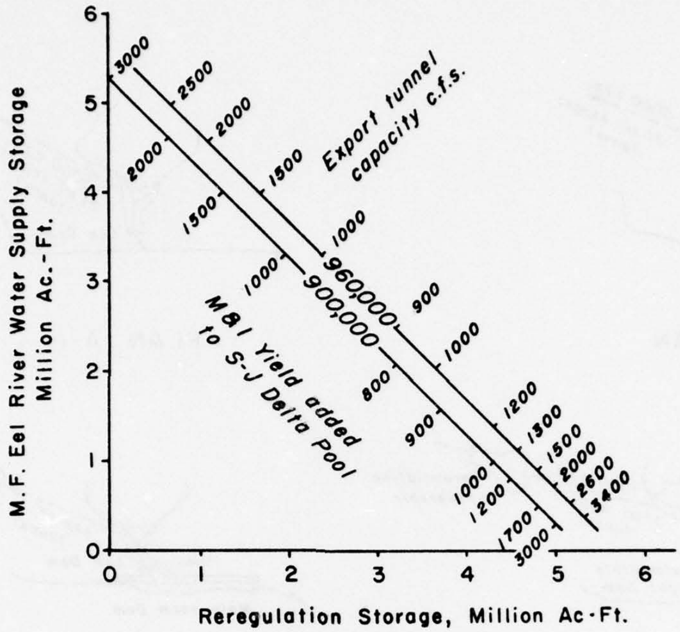
PLAN A-2



PLAN A-3

Plan A-1 consists of a lower dam at the same site as the basic plan but without inundating more than about 1,800 acres of Round Valley. This limits gross storage to about 570,000 acre-feet and only about 80,000 acre-feet of this can be utilized to store water for export. A 3,000-cfs tunnel is still required in order to prevent excessive loss of winter runoff. A holding reservoir on the Sacramento side of the ridge with 4.9 million acre-feet of usable storage is also required to reregulate flow to the specified demand schedule.

Plan A-2 provides complete protection of Round Valley by a dam at the mouth of the valley and saddle dams where necessary. Storage is limited by a maximum dam height of 700 to 800 feet and would still require a holding or reregulating reservoir on the Sacramento side of the divide. A 5-mile long drainage tunnel 22 feet in diameter would be required to insure Round Valley against flooding from runoff originating in the 100-square-mile watershed which drains through the valley. Total active storage between the two reservoirs was found to be essentially a constant of 5.3 million acre-feet for various sizes of the export tunnel and this provided an opportunity to investigate a wide range of storage combinations. The following diagram shows the relationship of these variables.



It is apparent from the above diagram that there are two combinations of reservoir storage for a given tunnel capacity, other than the minimum capacity, which can supply a specified yield. A cost analysis of various storage and tunnel combinations indicates that the minimum cost combination is a 1,000 cfs tunnel with 1.0 million acre-feet of water supply storage on the Eel River side and 4.3 million acre-feet of water supply storage on the Sacramento River side of the ridge.

Plan A-3 adds a dam and reservoir on the main stem of the Eel River to develop additional yield over and above the basic 900,000 acre-feet. This is applicable to any of the other plans but would result in different size reservoirs, pumping facilities and tunnel capacities. The purpose of this extension was to see how an adopted project could be modified to develop future water supply so that the adopted project would not add unnecessary costs to future developments. As an example, it was found that the most economical modification of Plan A-2 would require either an enlargement of the original export tunnel or a parallel system, either of which would be more expensive than to oversize the tunnel in the first place. This would depend on the discount rate and the period of time between construction of the added facility. With an added 3.5 million acre-feet of water supply storage in the third reservoir, another 525,000 acre-feet of firm yield could be developed in addition to over a million acre-feet released annually to the Eel River for local use and fishery mitigation. With the third reservoir added to Plan A-1, a pumping plant

with 500 cfs capacity would be required. The third reservoir added to Plan A-2 would require the same size reservoir and pumping capacity but would require a parallel tunnel of minimum size (approximately 10-foot diameter) or the original tunnel could be oversized by about 700 cfs. A higher lift from the Eel River reservoir to the Middle Fork Reservoir also would be required. These are some of the types of problems which face us. As shown on inclosure 1, more complex systems are to be studied in the future. These studies are being done in cooperation with the Department of Water Resources. At this time the most acceptable plan has not been selected.

Computer program 23-53 has been found to be extremely versatile in meeting our present study needs. We have not modified the program to accomplish some of the objectives which will be required before studies have been completed. These would include the energy requirements for lifting water from the downstream reservoirs into the upper reservoirs or the variation in delivery depending on a varying pumping head, pumped-storage energy generation, variation of tunnel diversion with varying reservoir stage, and recycling of the program with printout of final computations. As more precise answers are required, we will probably make some additions to the program or request the Hydrologic Engineering Center to make them. We have not graduated into the more sophisticated mathematical models which include cost and benefit inputs and outputs of optimal sizing of system elements even though the desirability of such programs is obvious.

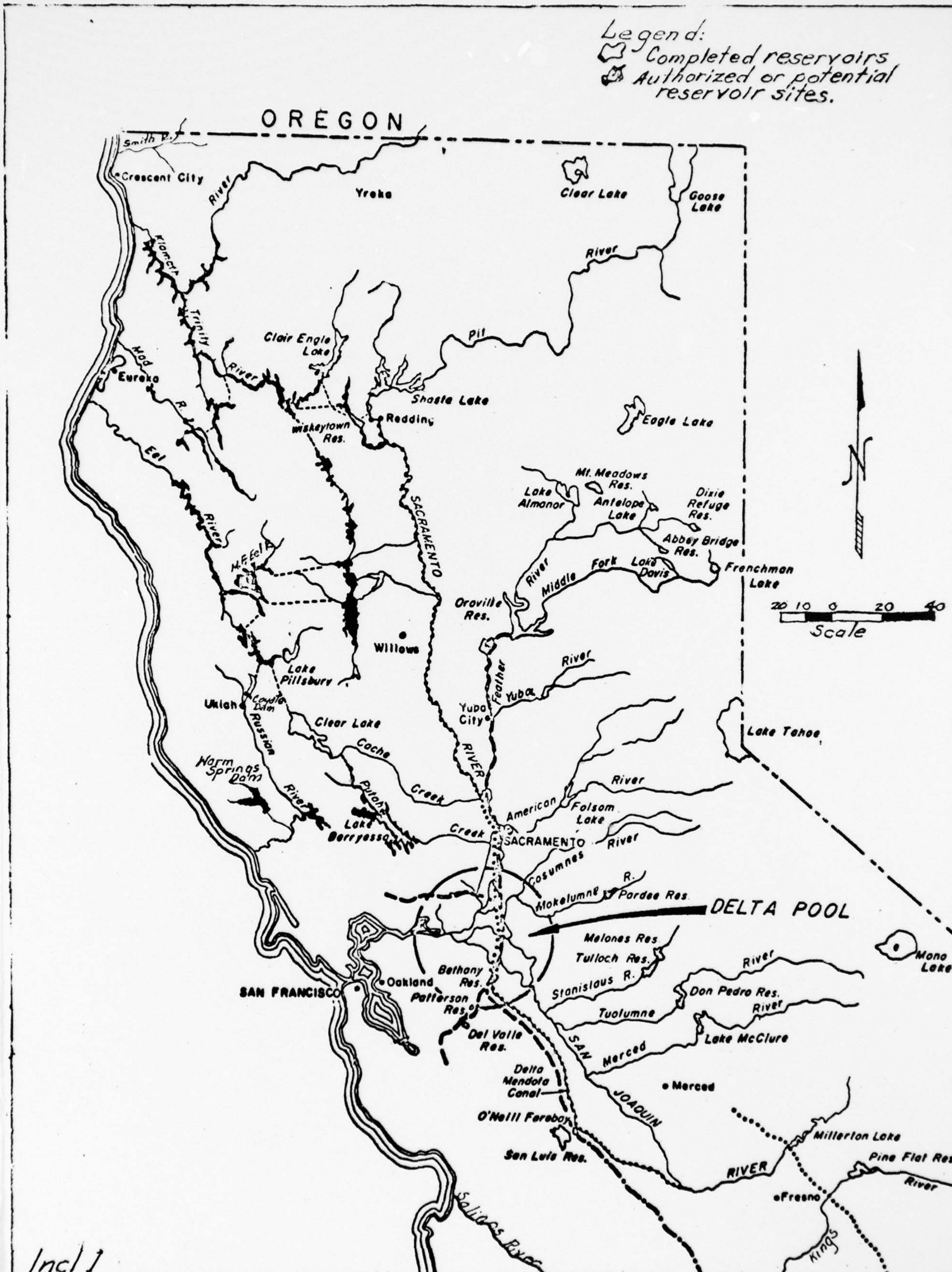
SUMMARY OF DISCUSSION

Compiled by D.C. Lewis[1]

The two-reservoir system program developed by San Francisco District personnel will accommodate the addition of more reservoirs to the Russian River system. The district program has been compared to HEC-3, using a simplification of the fishery release constraint. Results obtained were considered adequate for planning purposes.

The annual demands for the Eel River development study are presently determined as a result of operating the existing portions of the California Water Project for projected demands. The critical-period deficiencies are to be supplied from the Eel River.

[1] Hydrologist, Special Assistance Branch, The Hydrologic Engineering Center


Legend:
Completed reservoirs
Authorized or potential reservoir sites.
OREGON
Smith R.
Crescent City
River
Yreka
Clear Lake
Goose Lake
Klamath
River
Trinity
Clair Engle Lake
Pit
Mad
Eureka
R.
River
Shasta Lake
Redding
Whiskeytown Res.
Eagle Lake
Eel
River
SACRAMENTO
Mt. Meadows Res.
Lake Almanor
Antelope Lake
Dixie Refuge Res.
Abbey Bridge Res.
N.F. Eel R.
River
Middle Fork
Lake Davis
Frenchman Lake
Oroville Res.
20 10 0 20 40
Scale
Willows
Lake Pillsbury
Feather
River
Yuba
Yuba City
Ukiah
Coyote Dam
Russian
Clear Lake
Cache
Lake Tahoe
Warm Springs Dam
RIVER
River
Creek
American
Folsom Lake
River
Putah
Creek
Lake Berryessa
SACRAMENTO
River
Cosumnes
Mokelumne R.
Pardee Res.
DELTA POOL
Melones Res.
Tulloch Res.
River
Mono Lake
Oakland
Bethany Res.
Stanislaus R.
SAN FRANCISCO
Patterson Res.
Don Pedro Res.
Tuolumne
River
Del Valle Res.
SAN
Lake McClure
Merced
Delta Mendota Canal
JOAQUIN
Merced
O'Neill Forebay
Millerton Lake
San Luis Res.
RIVER
Pine Flat Res.
River
Fresno
Kings
Salinas River

Incl 1

SYSTEMS ANALYSIS FOR REGIONAL WATER SUPPLY PLANNING
THE NORTHEAST WATER SUPPLY STUDY

By

Lewis G. Hulman[1]

INTRODUCTION

The record drought of the early 1960's in the Northeastern United States has resulted in an inventory of water supply capability in the most densely populated and industrialized region of the country. All the urban centers from Washington, D.C. to Boston are included in the study area. The largest urban area, the northern New Jersey-New York City-western Connecticut region with an anticipated year-2020 population of 31.1 million (1965 estimate - 18.3 million), is the service area for the regional water supply systems discussed herein. System analysis of different existing and proposed impoundments in regional schemes was a cooperative undertaking of the joint venture consultants (Metcalf and Eddy-Hazen and Sawyer[1]) to the North Atlantic Division, Corps of Engineers, and The Hydrologic Engineering Center. The text of this paper discusses the method of analysis, the schemes studied and potential improvements in methodology without direct reference to any participant.

THE REGION

Capacities of the many existing water supply systems in the northern New Jersey-New York City-western Connecticut service area range from much less than a million gallons per day to almost a billion gallons per day. The sources of these many interconnected water supply systems range from small local surface impoundments and ground water supplies to large reservoirs. Some of the larger reservoirs are located in drainage areas as much as 150 miles from water users. Including the many industrial users, the 17.8 million people (1965 estimate) in the service area using public supplies require an average of 2.33 billion gallons per day.

About 500 public water supply systems serve populations ranging from fewer than 50 persons to over 8 million. Except for portions of New Jersey and Long Island, the larger systems obtain most of their water from surface impoundments. In addition, many of the distribution systems are interconnected. Projected average daily water supply requirements are shown in table 1.

[1]Hydraulic Engineer, The Hydrologic Engineering Center

TABLE 1

ESTIMATED AVERAGE WATER DEMAND[1]

Area		Average Demand in mgd			
		Present	Year 1980	Year 2000	Year 2020
Northern New Jersey		634	1380	1920	2550
New York		1483	3360	4130	5130
Western Connecticut		212	570	830	1090
	TOTAL	2329	5310	6880	8770

Most major supplies in the region were designed on the basis of criteria developed before the record drought of the early 1960's. For example, the largest system in the region (New York City) depends on three reservoirs in the Delaware River Basin for a major portion of its supply. These reservoirs were sized and operated on the basis of a recurrence of the drought of the early 1930's. The 1960's drought was much more severe and only through extensive operating changes and conservation practices was water supplied without interruption. One result has been a detailed reappraisal of existing and proposed developments in the Delaware basin[2].

The urgent need for the determination of potential sources of future water supplies prompted by the 1960's drought, and the many political subdivisions and constraints imposed thereby, resulted in Public Law 89-298: authorization of the Northeastern United States Water Supply Study. The North Atlantic Division of the Corps of Engineers is conducting the study.

THE STUDY

The purpose of this paper is to discuss systems analysis techniques used in analysis of surface water supply sources as part of a study[1] of all potential sources. In addition to surface water, other sources, including ground water, desalinization and weather modification were also considered in the study. As directed, the study has been made without regard to institutional constraints that could impair development of regional supplies.

Systems analysis techniques were applied to the determination of yields available from combinations of existing, modified and new surface impoundments. Similar techniques have been employed by others[2] to evaluate large facets of existing developments in the region. Simulation of reservoir operation in meeting specified flow requirements during a hypothetical recurrence of a selected period of streamflow record is the basic technique employed.

Engineering judgment was first used to screen out schemes definietly less productive (economically) than others. The screening left for consideration many potential projects in the Connecticut, Housatonic, Hudson, Raritan, Passaic, Hackensack and Delaware basins.

It was decided to investigate separately the different schemes generally included in each basin. The number of schemes to be studied in each basin was limited to about five, and sub-system alternatives were ranked on the basis of unit cost (dollars per million gallons delivered to the service area). Several plausible regional alternatives were then chosen from combinations of sub-systems, and systems analysis used to determine the increased yield potential available from the combination.

YIELD DEFINITION

The yield obtainable from a single project or multiple reservoir system is dependent on the definition. For the purposes of the engineering feasibility study, yields were determined on the basis of full depletion of water supply storage with no supply shortages during a simulated recurrence of the historical period of hydrologic record. The definition does not allow the selection of design criteria on the basis of the probability of a potential supply failing. It does, however, indicate the ability of a water supply scheme to operate without failure during a recurrence of a known period of sequential flow records.

HISTORICAL STREAMFLOW

The hydrologic record used was average monthly flow from October 1923 to September 1967 and covered the two most severe droughts in the region. Recorded monthly streamflow records for selected stations were supplied by the USGS. Many of the records contained the effects of existing impoundments and diversions. The streamflow effects of most of these structures were estimated and the records adjusted accordingly. In several instances, the historical effects on streamflow were judged either negligible, or future operation could be expected to be the same as in the past, and records were not adjusted. In addition, many of the records did not cover the entire period of study. Flows were generated [3,4] for these periods to complete records for the common base period.

Most of the streamflow records were for locations other than reservoir sites or control points. Linear relationships between the average monthly flow at one or more gaged sites and the incremental area flow at reservoir sites or control points were developed primarily on the basis of drainage area ratios. In many cases, examination of low-flow periods revealed that the relationships would produce periods of negative flow for drainage areas between reservoirs and control points. The relationships were then constrained to provide only positive values for intervening area flow.

Since the seasonal variability in demand can have a significant effect on yield[5], expected monthly variations in demand were specified. Table 2 shows the monthly variations used for potential service area supplies available from different basins and is based primarily on percent usage in selected areas of northern New Jersey and New York City.

TABLE 2

MONTHLY VARIATIONS IN WATER SUPPLY DEMAND

MONTH	PERCENT VARIATION OF AVERAGE ANNUAL DEMAND	
	Hudson, Housatonic & Connecticut Basins	Delaware, Raritan, Passaic & Hackensack Basins
October	103	105
November	100	100
December	100	95
January	96	92.5
February	96	90
March	92	92.5
April	93	95
May	92	100
June	100	105
July	112	107.5
August	109	110
September	107	107.5

SYSTEMS ANALYSIS

In the systems analysis, water was supplied for in-basin and service area needs. The local basin needs are those for water quality control, existing recreation, salt water intrusion control, existing hydroelectric power requirements, and existing and future local water supply needs. These requirements were supplied first in each system, i.e., they were met before water was made available for the service area. Water quality requirements were established at all reservoirs studied as a minimum

release of 0.2 csm, except for some of the existing New York City reservoirs (Rondout, West Branch, Boyd Corners, Ashokan and Schoharie reservoirs) where such releases were not considered to be required in the future.

The use of each reservoir studied is categorized as follows:

a. Local use. These reservoirs would be operated monthly for in-basin requirements. Only local and downstream requirements within each basin would be served by these projects.

b. Service area use. These projects would be operated for water supply to the service area after meeting immediate in-basin outflow requirements (0.2 csm minimum outflow requirements), if any.

c. Combined use. These impoundments would be used for both local and service area needs, with release priority being given to local needs.

d. Pumped storage reservoirs use. In addition to normal peak-period hydropower generation, pumped storage reservoirs would be used for service area needs. Greater than normal pumping during periods of high flow (diversion at estimated average pumping rates) would be followed by release of stored water during periods of low flow. In addition, these projects would be operated primarily for service area needs, and local needs supplied only if other reservoirs being used for this purpose in the system were empty.

Up to eight storage zones or levels were used in each reservoir to provide a means of balancing reservoirs in the system at the end of each monthly simulation period. The use of storage balancing levels allows the system yield to be determined during noncoincident periods of low flow from storage accumulated in previous periods of higher flow. The top two levels delineated flood control storage and were made equal for projects not operating for this purpose. The bottom two levels were used to define buffer storage, or storage to be used only after all conservation storage had been depleted. In addition, the zoning could be specified differently each month. Monthly variable buffer storage was used to set the priority of releases for the pumped storage reservoirs. This was accomplished by specifying water supply storage in the buffer zone during months in which pumping was required.

OPERATION

A series of repetitive computations was made during each month of sequential simulated reservoir operation. Each monthly computation series examined reservoir inflows, and diversion and release requirements, progressing in a downstream order. Individual upstream reservoir releases

were increased, if necessary, to satisfy requirements at each successive downstream point. The ability to exclude reservoir operation for specific control points was used where a reservoir was not intended to serve a specific need. Flow requirements in excess of intervening-area runoff and previously determined reservoir releases were allocated to upstream reservoirs serving specific control points in such a way as to balance storage in accordance with storage levels.

The monthly computations were repeated for twelve months, annual summaries and statistics determined, and the process repeated for the entire period of simulation.

The output of each simulation was examined to determine changes necessary in specified yields and pumped storage diversion rates required to achieve full system storage depletion without incurring any shortages in supply. The system was resimulated until either no supply shortages were noted, or until full storage utilization had been achieved.

BASIN SYSTEMS

Models of proposed schemes in the Connecticut, Housatonic, Hudson, Hachensack, Passaic, Raritan and Delaware basins, and existing New York City sub-systems were prepared for computer analysis. Initially, approximately five alternatives in each basin were prepared. Subsequently, many variations of each alternative were also studied. More than forty alternatives were examined. The alternatives ranged in size from one reservoir and three control points to 19 reservoirs and 32 control points.

Figures 1 to 8 schematically illustrate combined alternatives studied for each basin and the existing New York City systems. Figure 1 shows the relative location of each basin with respect to the service area. Figures 2 to 8 show each basin or sub-system. Figure 9 is a montage of all alternatives and is shown to illustrate the relation of alternatives to the service area.

THE PROGRAM

HEC computer program, Reservoir System Analysis (23-X6-L253)[6] was modified to accommodate methods of operation and priority of demands discussed above. In addition, the program was modified to allow simulation results to be in any units desired. Specifically, program output units used were million gallons per day (mgd) and million gallons (mg) for flow rates and storage volumes, respectively. The program is written in a generalized manner so that any combination of reservoirs and control points may be modeled. Limiting system size to any combination of 51 control points and reservoirs requires approximately 61,500 words of memory of the CDC-6600 computer.

COMBINED SYSTEM YIELDS

Regional plan system yields, the yields from combined basin alternatives selected for possible development, were determined graphically. For each regional plan a reservoir storage hydrograph was constructed for the two most severe low-flow periods (1930-32 and 1960-67). The total yield available to the service area was estimated from the sum of the sub-system yields, and the additional yield available from the minimum storage remaining in the combined plan. The additional yield available from the combination of sub-systems is the result of noncoincident periods of low flow. In all cases the 1960-67 period was the most severe. Comparison of the yields computed from the two periods did, however, provide an estimate of the relative severity of the two droughts.

SUMMARY OF RESERVOIR SYSTEMS ANALYSIS TECHNIQUES

Preliminary screening of projects was accomplished on the basis of rough economic studies to eliminate very expensive sources. Computer models of individual basin alternative surface water developments were used to determine the hydrologic performance of sub-systems in meeting local and service area needs. Descriptions of the physical characteristics of each impoundment, release requirements, constraints, operating criteria and sequential historical streamflows were used with the reservoir systems analysis computer program to determine, by repetitive computation, yields available to the service area.

Sub-systems were ranked in accordance with their expected economic merit (cost per million gallons delivered to the service area). Several plausible regional alternatives were selected for presentation from the ranking. Total regional yields were determined from the sum of sub-system yields and the additional yield available from storage remaining in different portions of the combined system.

POTENTIAL IMPROVEMENTS IN METHODOLOGY

To preface this discussion, it is necessary to point out that seldom will one encounter complex computer programs which do not require modification. In addition, principal working personnel are seldom all fully familiar with computer utilization and the methods being employed. Both of these areas are major obstacles to studies of this type and can cause serious communications problems.

As discussed, some linear relationships between streamgages used to compute average monthly intervening area flows did not produce acceptable results, particularly during low-flow periods. Since yield estimates may be significantly affected by such relationships, further detailed study is required.

Automatic determination of yields should be included in the computer program to speed analysis. A routine adjustment to pumped storage diversion rates would be required for such computer program recycling.

Economics could be used automatically in conjunction with the systems analysis techniques discussed to measure the performance of selected plans. In addition, economics could also be used to refine the size of projects in any scheme, or to analyze different alternatives.

Linear and dynamic programming techniques hold promising possibilities for the future in project screening processes, in construction staging studies, and in the refinement of the size of projects in regional plans.

Substantial computational effort would be eliminated by modeling only regional alternatives. A basic model of existing reservoirs, economically dominant potential projects and local requirements would be developed initially. Alternatives of this basic model would then be analyzed to determine the best mix of marginal projects. The same general technique could also be used in the staging of project construction. It is believed that the technology for such an undertaking is now available.

The use of historical streamflow to determine system yields should be combined with similar analyses of stochastic flows to provide design criteria on a probabilistic rather than historic-performance basis.

Optimization of reservoir system operation should be undertaken as part of the continuing planning process. The increase in expected yield could be substantial.

REFERENCES

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2. Hulman, L.G. and Erickson, David K., A Hydrologic Water Resource Modeling Technique, paper presented at 17th Annual ASCE Hydraulics Division Specialty Conference, Logan, Utah, August 1969.

3. Beard, L.R., Monthly Streamflow Simulation, The Hydrologic Engineering Center, Corps of Engineers, July 1967.

4. Quirk, Lawler & Matusky Engineers, Surface Water Capabilities of Northern New Jersey Basins (NEWS Study), December 1968.

5. Fredrich, A.J., Techniques for Evaluation of Long-Term Drought, paper presented at ASCE Water Resources Conference, New Orleans, La., February 1969.

6. US Army Corps of Engineers, The Hydrologic Engineering Center, Reservoir Systems Analysis, Generalized Computer Program, December 1968.

SUMMARY OF DISCUSSION

Compiled by H. E. Kubik[1]

There was some discussion of the means of evaluating the large volumes of output in the NEWS study for each successive approximation. The 1960-1967 period was the most critical; therefore, the performance of the system was checked through that critical period. The relation of any shortages or unused storage during that period to the demands for the period would indicate the manner in which the operation should be modified.

Modification of the simulation program to allow automatic cycling would require the selection of some performance criterion by which to determine new values of the variables for each successive simulation.

The advantages and necessity of including the whole NEWS system in the simulation rather than each subsystem separately were discussed. When considering the dimensionality problem associated with linear and dynamic programming, this might not be feasible if those techniques were to be used. Nevertheless, there are disadvantages to considering each subsystem separately. The critical drawdown period does not occur at the same time at each of the projects and probably would not be simultaneous in the future. Therefore, selective basin withdrawals will provide a larger total system yield than the sum of the yields of each subsystem. A complete system analysis must consider the transmission capacity between the various basins and the service area.

Mr. Rockwood asked Mr. Beard to comment on the reasons that stochastic hydrology would be useful in reservoir system analysis. Mr. Beard thought there were three major reasons:

1. It can shed some light on the frequency of the worst drought of record. In some cases, such as the drought of the 1930's in the Missouri River Basin, it is suspected that the drought might be far rarer than could be expected in the 60 or 80 years of record.

2. It can provide a variety of sequences by which a design can be tested. There is a tendency to tailor a design to the particular sequence of record, and rules thus obtained might not work out as well as anticipated when a different sequence occurs.

3. Stochastic hydrology is probably most useful in staging a system as needs for water increase, which is probably the way in which future systems will be planned. A single (historical) sequence would be completely

[1]Hydraulic Engineer, Special Assistance Branch, The Hydrologic Engineering Center

inadequate for sequential staging analysis, since the time of drought would be preceded by much construction, and there would be no construction during the drought. Testing a staging plan with a large number of sequences would demonstrate the need for rather uniform build-up, since drought periods cannot be forecasted.

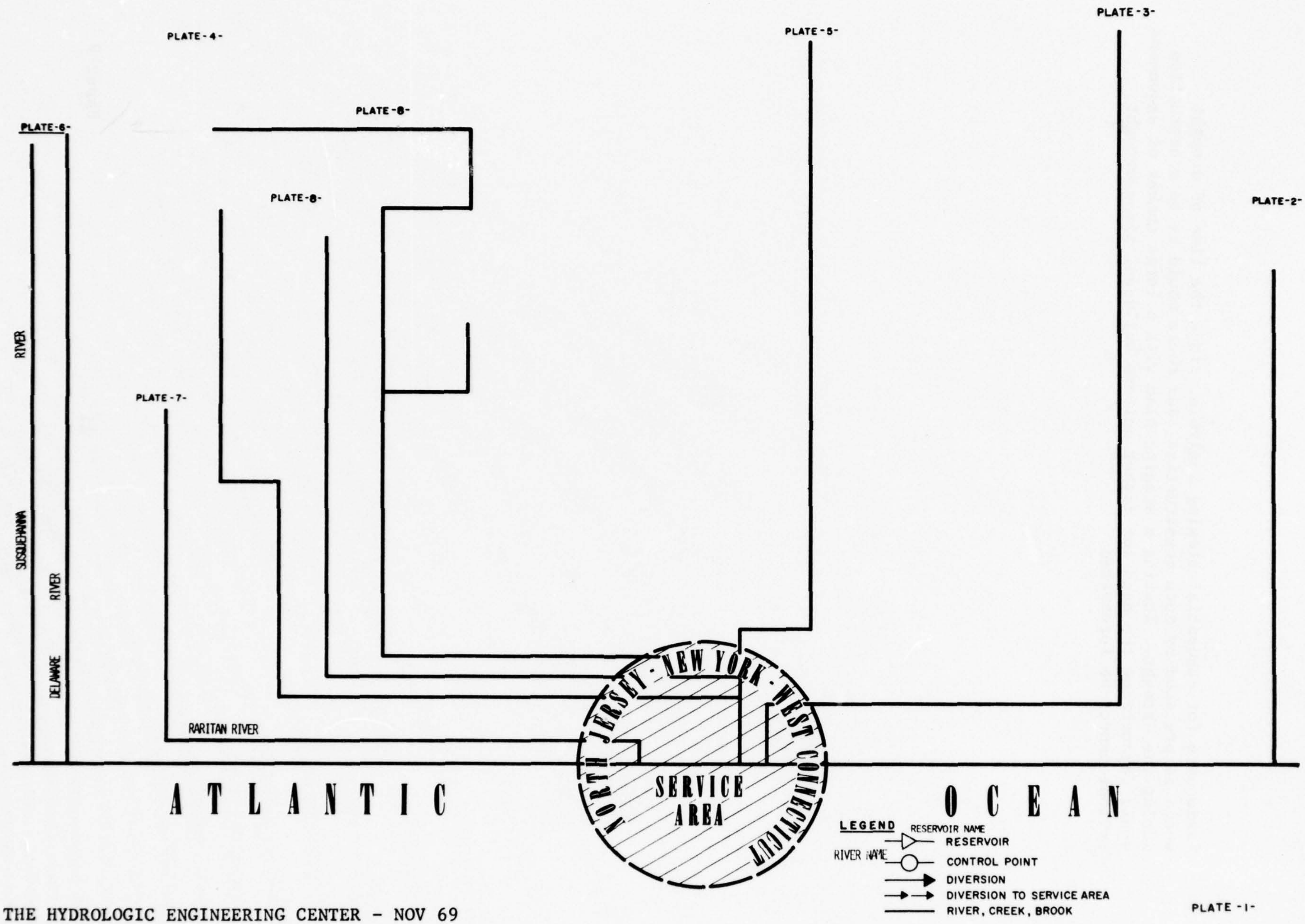

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PLATE -1-

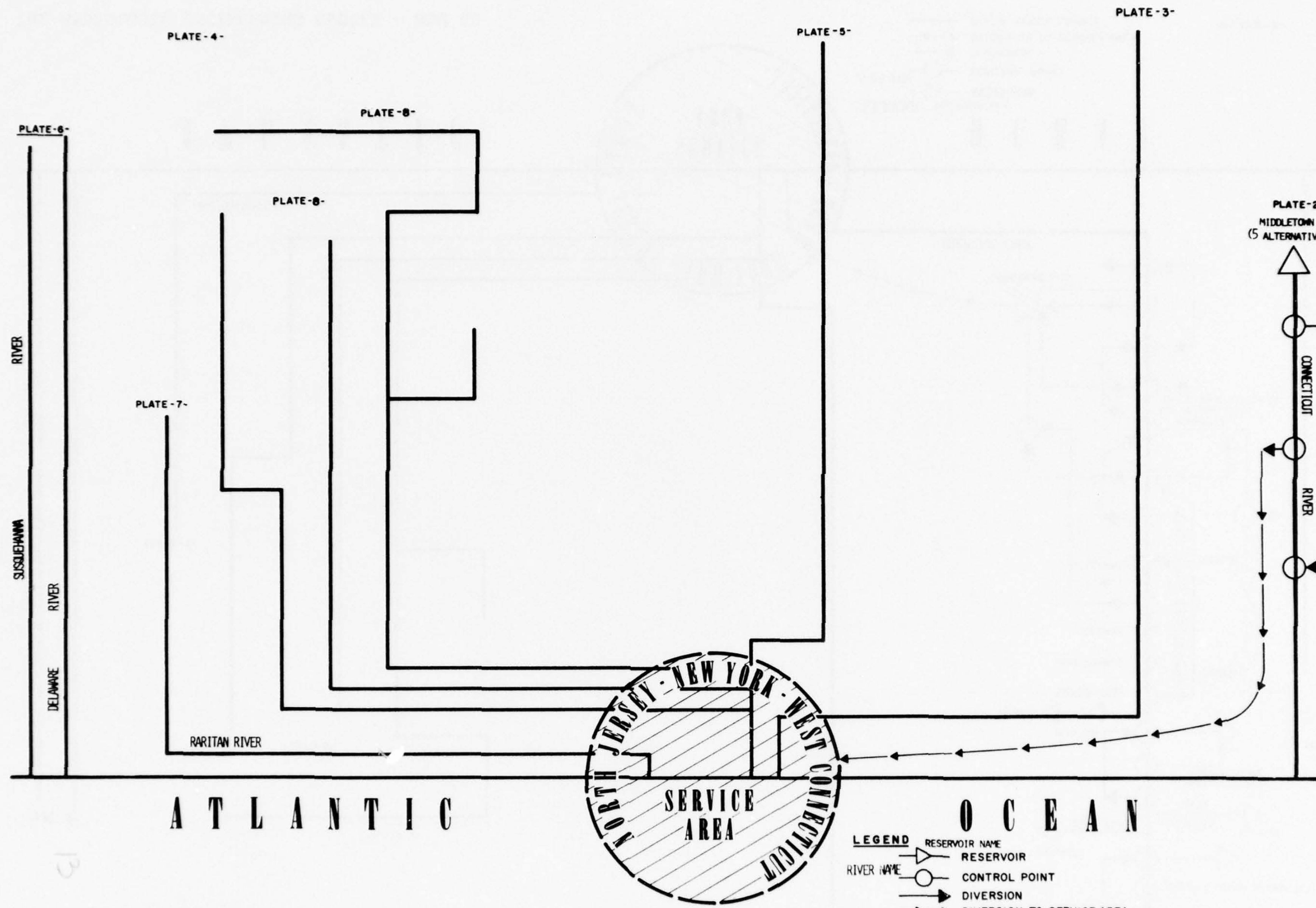

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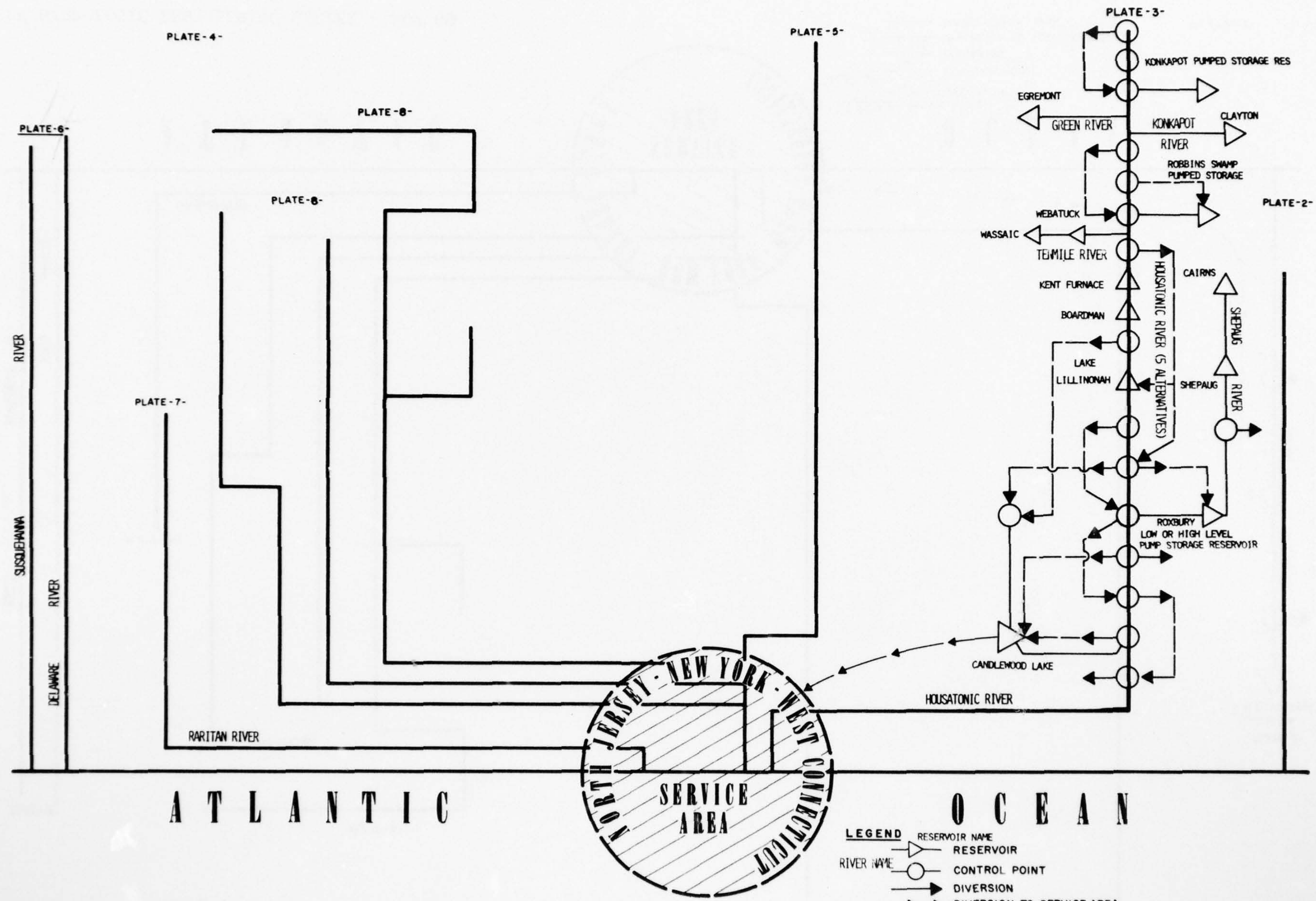
PLATE -2-



THE HYDROLOGIC ENGINEERING CENTER - NOV 69

PLATE - 3 -

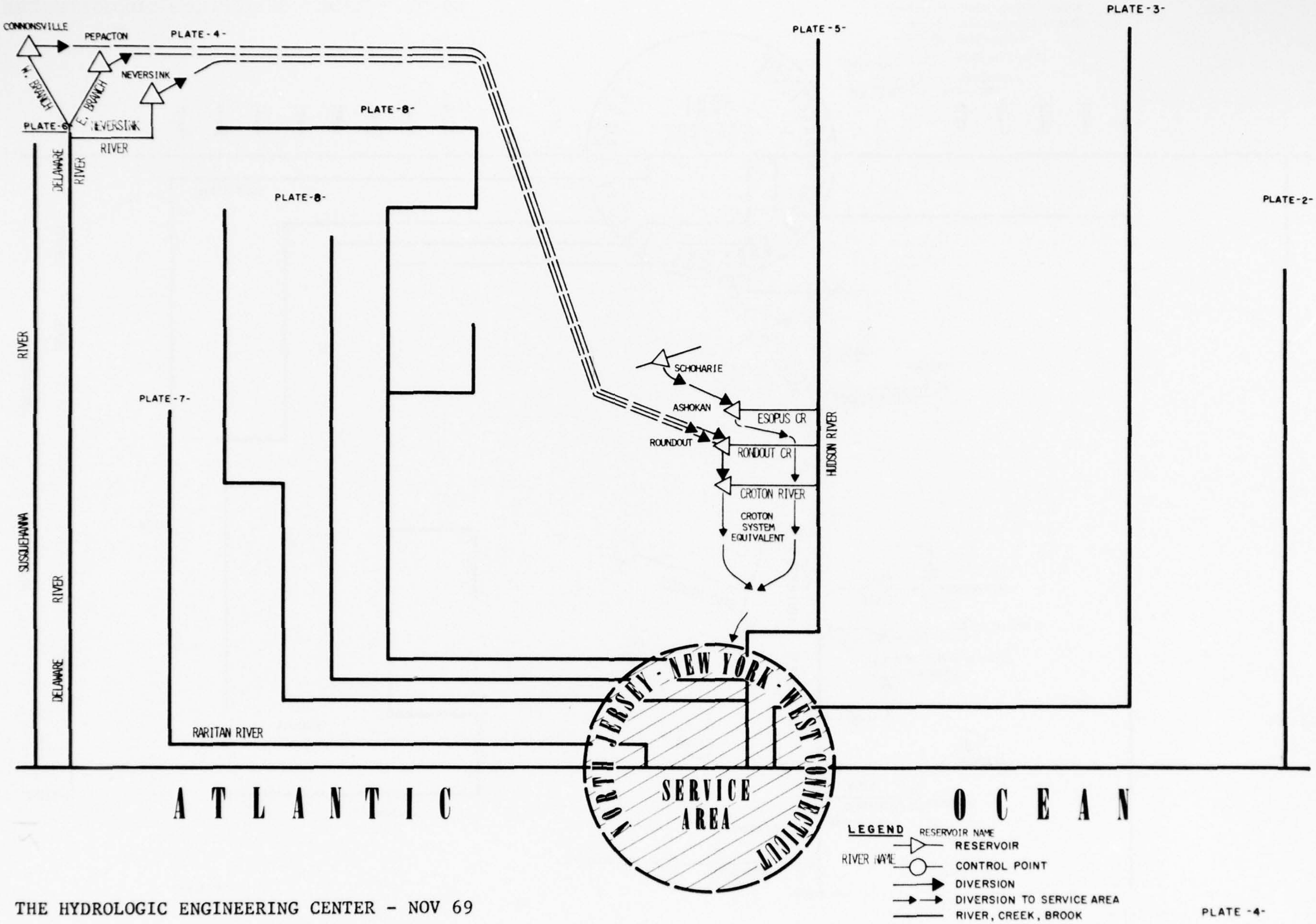


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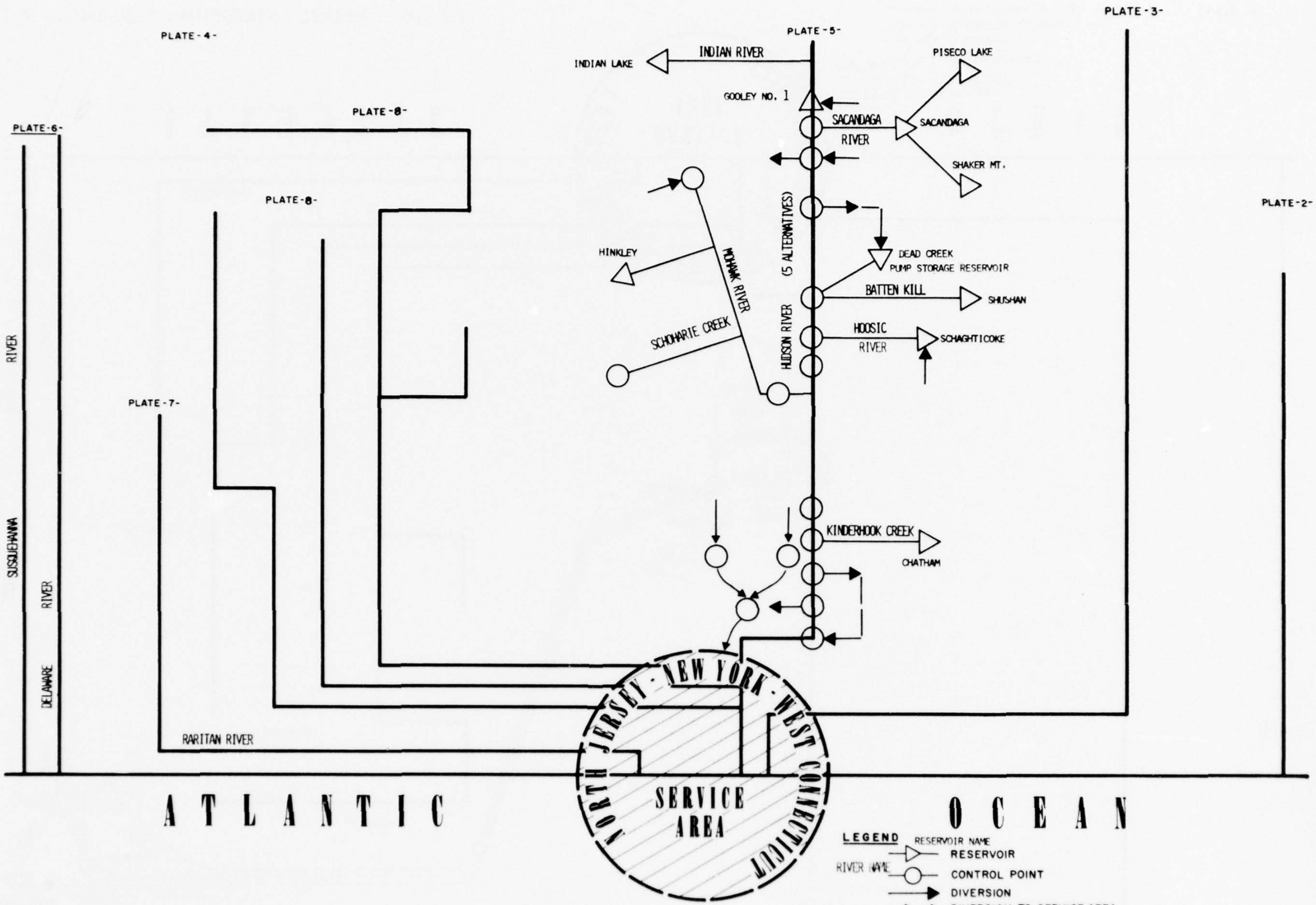
PLATE -4-



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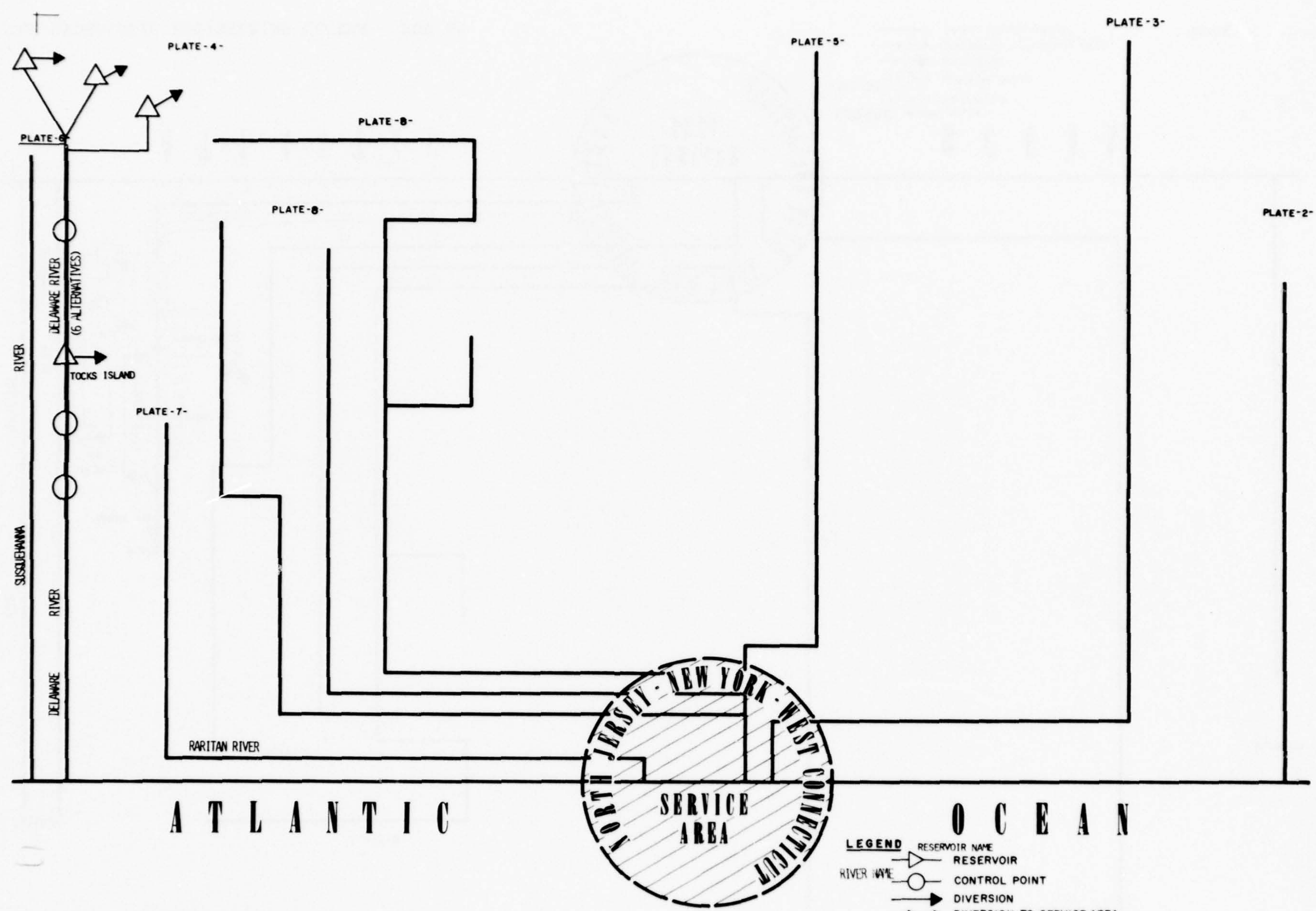

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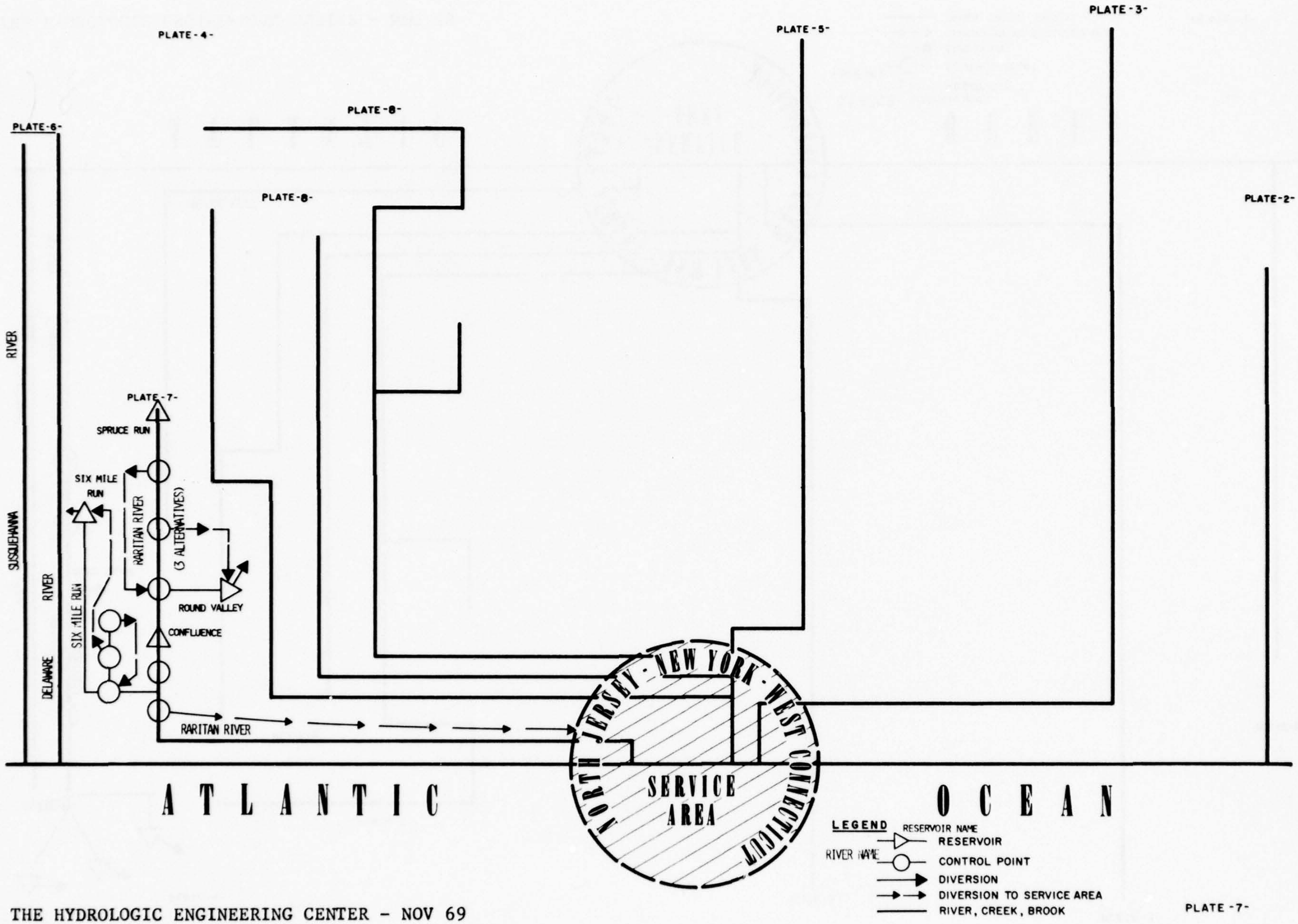

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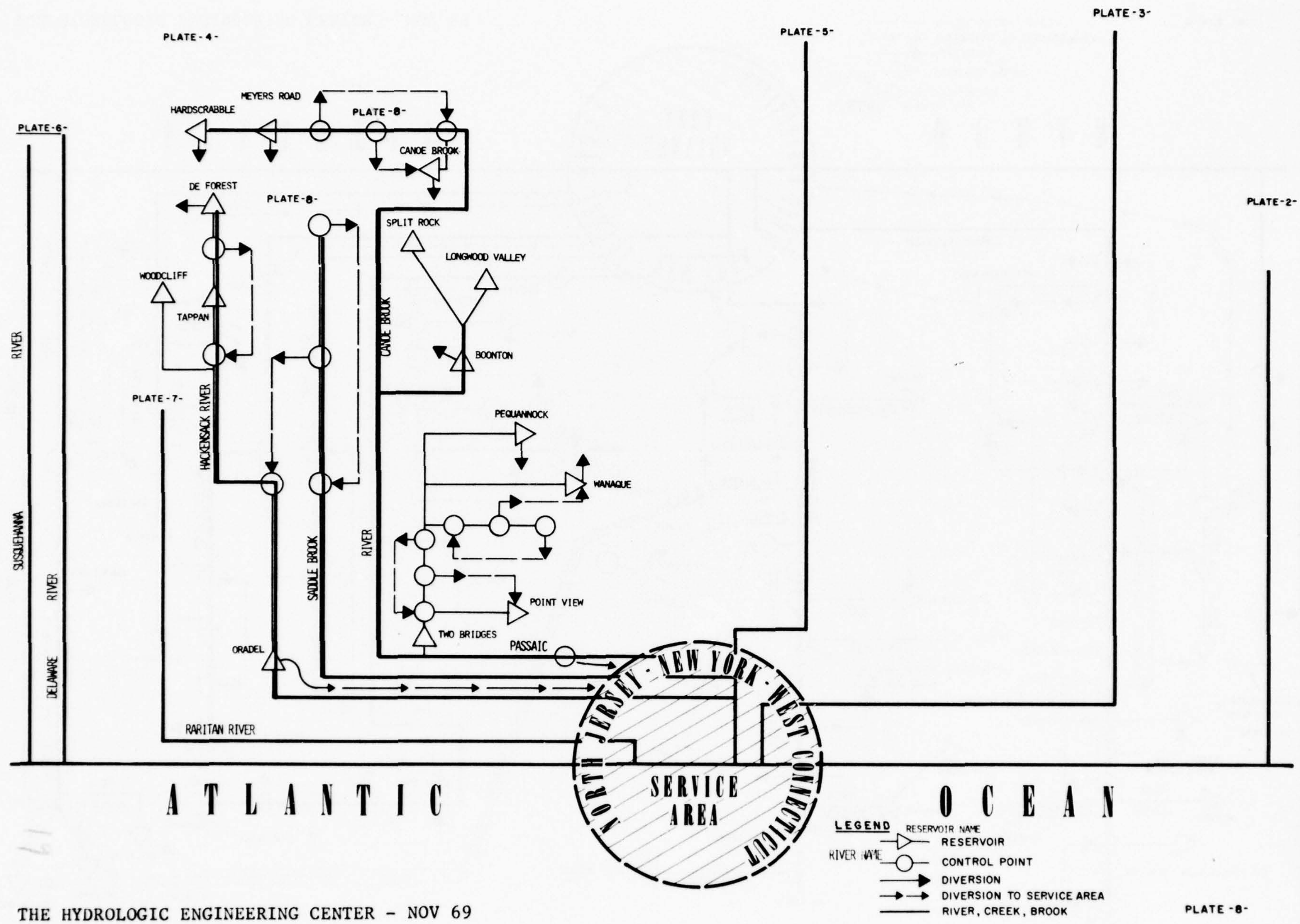

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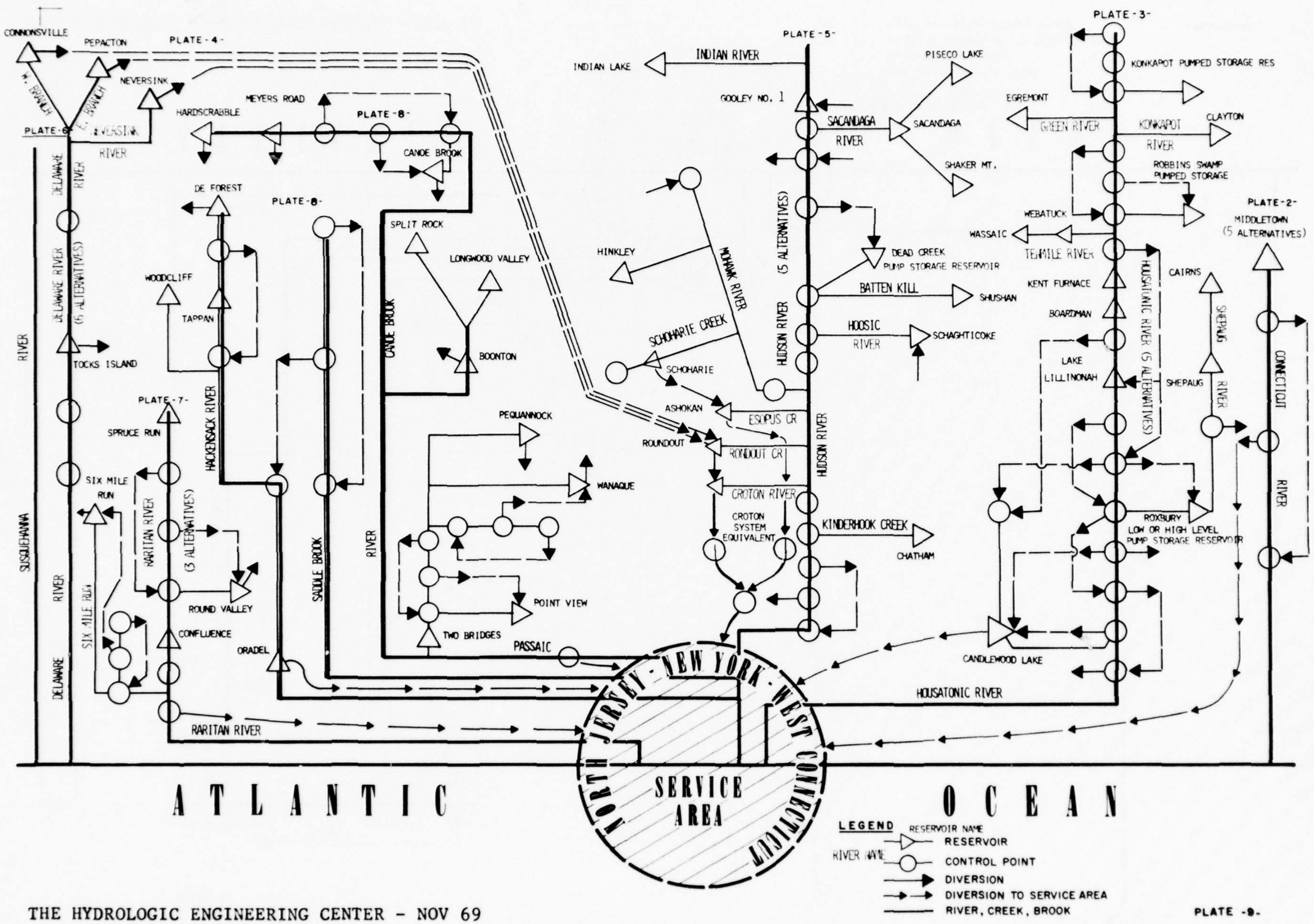

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PLATE -9-

SYSTEM ANALYSIS AS A BASIS FOR PLANNING
COLUMBIA BASIN PROJECTS

by

David J. Lewis[1]

INTRODUCTION

For over 40 years projects on the Columbia River have been studied as integral parts of a regional system planned with the overall objective of the optimum multipurpose use of the river. Specific goals of this overall objective change, however, as conditions change in unanticipated ways and as the public view of optimum use changes.

In the early planning of the Columbia River and its major tributaries, irrigation and power development were the paramount goals. For example, the first comprehensive "308 Report" on the Columbia River, submitted to Congress in 1932, concluded that flood control storage was not justified. However, before the review of the 308 Report was completed in 1948, flood control was a major developmental goal, and the anadromous fish run was recognized as an important enough consideration that a definite program for their preservation was recommended for Congressional recognition in the 1948 report. In recent years, the increasing public awareness of environmental values has required that these be included as a major consideration in the system analysis.

The hydrologic character of the Columbia River makes the use of storage for these various requirements unusually compatible, a compatibility which made it possible to add the requirement for flood control with only modest adjustment to the system by supplementing, rather than discarding, earlier plans. The Columbia River is unique both in the pattern and the predictability of the annual flood flow. The natural flows are low in the winter, while the precipitation in a large part of the basin is being stored as snow. The heavy runoff starts when the warming weather in the spring melts the snow and runoff increases to a peak in May or June. The volume of flow during the 5-month snow runoff period from April through August is 70% of the annual flow. Its volume can generally be forecast within less than 10% far enough in advance to permit effective utilization of the storage releases.

DEVELOPMENT OF SYSTEM STUDY CAPABILITY

Past studies have adequately served the needs of their time, but the rapid development of the system and increasingly complex objectives have required improvement in the study capabilities.

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The regulating goals for power and flood control are compatible enough that the control of the system regulation study may be guided largely by the more complex regulating requirements for meeting the system's power load. Detailed examination of flood control regulation will not often require changes which would significantly affect the results of such regulations, particularly if the experience of other flood regulation studies are reflected. The regulating goal for both power and flood control is to store the predictable flood flows and release them during the period of low natural streamflow. Flood regulation is satisfied when the flows are reduced to non-damaging levels, but power regulation would reduce the maximum flows still further when possible, to a level which could be passed through the turbines and used for power generation.

The principal conflict in goals is a matter of assurances. Power's preference is to have sufficient storage space available to contain probable flows, balancing the possible loss through spill of unanticipated high flows against the danger of not filling and the cost of the repeated loss in energy and capacity through reduced head. Flood regulation's preference is to have sufficient storage space to have the assurance of not losing control and creating unnecessarily damaging flows, even if the damages are small.

The early studies, during which irrigation and power were the dominant objectives and the power potential appeared far greater than the need, were general with respect to the location and operation of storage. The effects of storage regulation were, nevertheless, considered in analyses of specific projects. General as these studies were, they satisfactorily identified the location of dams developing the main stem of the Columbia downstream from the Canadian border. Later studies have supported those findings, and today the projects are in operation, with only one significant modification. Two dams have been used to develop one river reach in place of the one dam proposed originally.

As the need for flood control became more apparent and a large power requirement became imminent, specific basin-wide systems of storage and run-of-river projects were studied in preparing the 1948 Review Report. In each system, the storage was regulated to optimize the benefits. Systems as large as 20 projects were regulated on the basis of a 20-year historical streamflow record. These regulations were laboriously produced with the aid of a desk calculator, using average flows. They were augmented by studies of a few of the major historical floods to establish flood-related design and real estate acquisition criteria and to determine flood control benefits.

These specific system regulations and flood studies made a more definitive analysis possible, but the time-consuming nature of hand regulated studies limited regulations to a few alternative systems. Other alternatives were studied by the relatively unsatisfactory procedure of adjusting results

of the basic regulation or by attempts at evaluating increments. The adjustment could seldom be effecitvely supported and were subject to biases introduced in the assumed effect of the adjustment on the remainder of the system. In a hydroelectric system operated to meet the system load, the operation of one project inevitably requires compensating changes in others, but the other changes cannot be clearly identified without a revised regulation of the system. As a result, it was difficult and often impossible to reach agreement between government agencies and power utilities on the capability and value of power projects, particularly storage projects. In addition, the absence of a specific regulation prevented adequate consideration of the impact of system changes on the environment.

SYSTEM REGULATIONS BY DIGITAL COMPUTER

The advent of the digital computer made it possible to enlarge greatly the area and detail of consideration and to further systematize procedures. The basic tools became computer models of river systems and the basic method became comparison and evaluation of simulated regulations of alternative systems. It has become possible to study many alternative systems and to examine the value and effects of alternative amounts of storage and capacity by studying each as a part of a total system. The increment is now studied by comparing alternative systems rather than by estimating incremental effects. Assumptions have been minimized and agreement between government agencies and electric power utilities on power capabilities have become routine.

The improvement in system studies made possible by the digital computer was instrumental to implementating the Columbia River Storage Treaty with Canada, which required estimating in 1963, for each year from 1968 to 2005 the power generation downstream in the United States due to the storage operation.

In spite of our greatly improved study capability, the increasingly complex requirements tend to outpace our improvements. The present demands on the system storage require that it be operated to meet irrigation requirements, to assure flood protection, and to maximize the value of hydroelectric power generation. At the same time, we must give increasing attention to the requirements of fish life, recreation, and other environmental considerations, including river temperatures and the day-to-day regulation of storage during the flood season and possibly during the initial periods of storage draft.

The study process is further complicated by the increasing requirements for peaking installations at run-of-river projects. The use of this increased capacity in meeting the rapidly changing daily load results in correspondingly rapid changes in pool and river levels. These changes, if too severe, create undesirable conditions for navigation and recreation, but constraints to protect these interests, if too severe, limit the

usefulness of capacity in meeting the system's load. Study of these conditions to determine a correct balance between peaking and non-power interest can only be accomplished with an hour-by-hour examination of the river.

System regulation studies are made for planning future additions to the system, for establishing operating criteria, and for planning system operations. Computer models of the system are required for all. Because of the interrelationship of the three, a system model which is appropriate to one will also be appropriate to the others and the best model will be the one which can most accurately represent the actual system operation with the least study effort. Projects must be designed to meet the requirements of operation throughout their economic lives, and these requirements can only be determined by system regulations. The requirements will change as the region's power system changes from a nearly pure hydroelectric system in which the hydro projects carry the base as well as the peak load to a mature hydrothermal system in which the thermal plants will carry most of the base load and the hydro projects the peak. Good design requires a good appraisal of these changing conditions. The system regulations must be detailed enough to reflect significant operational conditions but no more detailed than is necessary. Many of the study requirements will be satisfied with a model which uses increments of monthly average flow and others require analyses of smaller increments of time. A family of computer models has been developed by the North Pacific Division to satisfy each need with the most efficient model, which will generally be the one using the longest acceptable time interval and the least complicating detail.

HYDRO SYSTEM SEASONAL REGULATION PROGRAM

Most of the economic studies of the projects and most of the operational planning studies are dependent on the basic seasonal regulation studies. The seasonal regulations are made with the Hydro System Seasonal Regulation program (HYSSR). The model is general and is set up for any specific system by preparing a "run file," by the introduction of the system configuration, fixed constraints such as minimum flows or maximum pool levels for specified periods, and the number of generating units at each project. Other data such as streamflows, plant characteristics, discharge-elevation relationships, tailwater tables, and reservoir evaporation losses, are transferred to the "run file" by the program from a permanent file. A 30-year flow period, 1928-29 through 1957-58, is now used by Government Agencies and Power Utilities in the Pacific Northwest. The average monthly flows for that period have been modified to reflect anticipated irrigation diversions and return flows.

With the "run file" prepared, a regulation can be made in its simplest form by introducing appropriate reservoir storage changes for each time period and comparing the computed generation with the load. Adjustments

can then be made until the generation matches the load. The most adverse flow periods are studied first. One will be found which will permit less energy to be generated than any other, and this is identified as the "critical period." The critical period is studied generally by a trial-and-error process until the regulation is found which produces the maximum power during that period when shaped to the region's load. While this requires a series of trial regulations, there are a number of built-in computation aids which minimize the adjustment effort.

The average energy generated in this critical period becomes the system's firm energy capability. The month-end storage levels during the critical period become the critical periond rule curves and set a limit below which no reservoir can be drafted unless greater draft is necessary to carry firm loads. These curves guide the regulation through the fall months when storage draft is necessary to carry power loads, but before volume forecasts can be made effectively.

By January, volume forecasts are dependable enough to permit their use, when properly discounted for error, in guiding the regulation of storage in subsequent months to a level which assures later filling of the reservoir. Again, reservoirs may be drafted below these levels only when necessary to carry firm load. These assured refill levels are calculated for each month from January through July by an auxiliary program using forecasts of runoff volumes prepared by the River Forecast Center of the Portland Weather Bureau for each of the 30 years included in the studies. The critical-period rule curves and the refill curves are supplemented as approriate by limiting upper rule curves which force an orderly draft of storage if the water is not needed for power generation. The upper rule curves are particularly desirable in high-flow years during the early development of the system when there is insufficient thermal energy to be replaced or other secondary energy markets to force the draft of reservoirs to their critical-period rule curves and assured refill curves. Regulations made with this program using average monthly flows (half-month averages are used for the beginning and final months of the low-flow periods) are satisfactory for the determination of firm and average energy and reflect quite well operating conditions during periods and years of low flow. They leave unanswered, however, a number of questions about how well the energy computed with monthly average flows represents the energy which will be usable for meeting firm loads in the day-to-day operation during the month the river declines to a level which requires storage draft. It also leaves doubt as to the accuracy of the month-end elevations during the summer months of the high-flow years. These questions can only be answered by the detailed regulation of the system with the SSARR program described in Mr. Rockwood's paper "Application of System Analysis Techniques to Project Operations." To be meaninful, studies with this program which normally uses a 12-hour time period on Columbia River studies, would start at the beginning of the flood season from elevations determined by the monthly regulation program. Due to the great number of

system regulations that are required for planning studies, it is presently impractical to regulate all flood periods in all regulations with the SSARR program.

The SSARR regulations are being used increasingly to study questionable periods of system regulations, and the results of these studies will be reflected as appropriate in the HYSSR regulation by the introduction of month-end elevations as input data.

When the regulations are being used for planning future system additions, the installation of future units assumed in setting up the initial run file will usually require adjustment in the course of the study. In initiating the regulation, it was necessary to identify the number of units installed at each project, yet it was not possible to determine the optimum number or location of future units until the regulation had been completed. After the firm energy is computed, it is possible to determine the system's total capacity requirement. The system's total hydrocapacity must then be modified by adjusting the number of units at some projects to provide the total required. Only after regulating throughout the 30 years is it possible to determine the most economical location of the units. The hydroelectric system's total requirement is that part of the system's total requirement which cannot be met by the thermal plant installed to make up the difference between the hydroelectric system's firm energy and the system's total energy requirements.

When the system regulation is completed, it may be found that too few units were installed at some storage projects and that the limited installation restricted the draft of storage at times and unnecessarily required misoperation of other projects. The regulation will also determine the energy lost at each project because of limited installation. The relative loss of energy due to the absence of a particular unit, together with the relative cost of that unit, determines its relative economic justification. The relative justification of each unit in the system is determined by the Unit Analysis Program. When the system regulations are being used for planning the system's operation, the unit installations will be known, and these adjustments are not necessary.

UNIT ANALYSIS PROGRAM

This program, on the basis of incremental power plant cost data furnished as input and with the monthly output of the HYSSR program, finds the incremental cost of units and groups of units added sequentially starting with the first unit at each project. It computes the energy added incrementally by any unit in the sequence and deducts the value of that energy from the incremental cost to find the net cost of capacity of that unit or the net benefit if the incremental energy value is greater than the cost.

The net cost determination can best be illustrated with the use of a hypothetical power project. The power plant has been constructed with ten units installed, substructure has been completed for five more units and space has been provided for an additional five. The investment in the ten units and five completed substructures would not be relevant incrementally, since it is now a "sunk" cost, but the incremental cost of completing each of the five remaining units would be entered in the computer. At the time the future substructure is built, it will be completed for all five units so that the minimum investment necessary to the addition of Unit No. 16 would include the substructure for all five units. The incremental cost of Unit 16 then is the cost of a completed Unit 16 plus four substructures and therefore very high; the cost of Unit 17 is only the cost of completing that unit and the cost of the Unit 16-17 group is the costs of Units 16 and 17 plus a three-unit substructure. The program computes from the initial and incremental investments the cost of each unit (Units 11 through 20) and each group (Units 16 through 20) so long as the addition of a unit to a group reduces the net cost. In the case of Units 11 through 15, the incremental costs of each unit would be nearly the same but the energy associated with each unit added sequentially would be less, since it would be used in a position higher in the flow duration curve for that project. With a near constant cost and a decreasing value of energy, the net cost of each unit (12 through 15) would be higher than the previous unit and they would not be grouped. The heavy loading of substructure costs associated with the first unit gets spread increasingly as the size of the group increases. The cost of groups of Units 16 through 20 would therefore decrease as the number increased, unless there were marked differences in incremental energy, and group costs would be computed for each group from groups 16 and 17 to groups 16 through 20.

After these net costs are computed for each uncompleted generating unit and relevant group of units in the system, they are listed sequentially from the unit or group having the highest benefit at the top to the unit or group having the highest net cost at the bottom. The program then examines all units included in the regulation and searches the list to see if there are less costly units or groups unused than those used, and if so, it indicates changes that should be made. Subject to other considerations such as peaking restrictions due to limited downstream pondage, the unit installations are revised and the regulation is re-run.

During the period that the system is largely a hydroelectric system and the load carried by the hydro system is substantially the same as the total system load. The peaking requirements during this period are not severe enough to require detailed investigation of pondage so system regulations augmented by the Unit Analysis Program, and a little judgment satisfy the needs of scheduling added units.

Thermal plants will carry an increasing share of the base load in the future, however, and hydro generation will be moved increasingly into

the peak. The peaking limitations due to physical and environmental considerations have become increasingly significant in the proper scheduling of capacity, and detailed analysis of the daily operating characteristics of the system is now essential to planning future units.

HOURLY LOAD DISTRIBUTION AND PONDAGE ANALYSIS

For this analysis, a program has been developed which is normally used for studying selected weeks from the system regulations. Input data include plant characteristics as applicable to instantaneous rather than average monthly conditions; storage data for "run-of-river" as well as seasonal storage reservoirs; tailwater characteristics including a "lag" simulation feature; travel time from project to project; the system load for a 7-day period in hourly increments; the average flow at each project for the week under study; and storage content for seasonal storage projects. The last two items are usually derived from a selected month of a seasonal regulation study.

The program divides each hourly load among the participating plants in such a manner that plant capabilities and limitations are not violated and that average weekly flows are exactly utilized; i.e., pondage reservoir contents are returned to their initial values at week's end. A degree of optimization is attained by operating all pondage reservoirs as near to their full level as conditions will permit. Unneeded capacity is set aside at those plants having the lowest plant factors (average energy divided by plant capacity), thereby relieving undue hydraulic imbalance.

It then computes the pool levels, generation and tailwater elevations by hours, tabulates and prints a chart of each for each project. The program summary indicates any pool overdrafts, and maximum hourly and daily changes in tailwater and forebay elevations. It also indicates the potential energy stored in the system's ponds and reservoirs, so that the efficiency of one operation can be compared with that of another operation meeting the same loads with the same flows. The combination of this program and the unit analysis provide a greatly improved capability for scheduling unit installations and for establishing the effectiveness of any units being studied in meeting the loads.

The Hourly Load Distribution and Pondage Analysis program's effectiveness is presently limited by the substitution of a travel time for a routing procedure. A more detailed hourly program including flow routings has been developed for use in operating studies and in planning studies where more detailed analysis of a few projects is desired. Preparation of input data for this program is very time-consuming, so it is presently used to supplement the more general program. It is presently being rewritten more specifically for use as an operating program, but also incorporating features which will facilitate greater use as a supplemental planning program.

SUMMARY

A complete system analysis of the Columbia River System for planning additions to the system requires the study capability of the above family of programs and the assembly of considerable cost data. Data must be assembled on the incremental costs of adding new units at all projects in the system as well as all new projects being studied. They must be in sufficient detail to permit their adjustment as the scope of the project is varied. Benefits and information on any unevaluated environmental considerations which are affected by the operation must be assembled.

Power benefits are measured by the lowest-cost alternative means of meeting a similar load. The best possible means of evaluation, therefore, becomes the substitution of an alternative of the element being evaluated in a system regulation and the determination of its cost. To make this type of evaluation, the costs of all feasible alternatives are needed. If only a generalized power benefit is provided in a form which does not permit adjustment to reflect the specific requirement of the load it is servicing, much of the advantage of a system analysis is lost.

Correspondingly, flood control benefits should be stated in a way which permits them to reflect the true differences in value of alternative patterns and amounts of stream regulation.

The optimum scope of each project is determined by evaluation of each increment studies and with a view to the effect of each increment on the environment.

An effective study cannot be made by combining in the final stage regulations made without knowledge of costs, benefits, or environmental impact and costs developed independently from the regulations. Optimum project design, optimum project regulation, costs and benefits are so interwoven that they can only be developed as they are studied together in a System Analysis.

SUMMARY OF DISCUSSION

Compiled by R. G. Willey[1]

There was some discussion of the validity of operation criteria based on studies of historical data where flows are known, since future flows cannot be forecasted accurately during actual operation. It was pointed out that a realistic set of rules and forecasts are used in the Columbia River studies, in order to simulate realistic conditions. The guide curves determine the operation in a systematic manner.

Some question arose as to the adequacy of the monthly operation study, since power and flood control are greatly influenced by short-period variations. It was brought out that hourly routings are performed for selected weeks during the critical drought period to ensure that there is sufficient pondage at run-of-river projects to meet peak demands.

A discussion of the critical drought period for the Columbia River studies revealed that the critical duration is now 7 months, but when storage is doubled, the critical duration will increase to about 43 months.

Since almost all power in the Northwest is hydropower, there was a question as to any possible use for surplus or secondary power. It was explained that secondary power is marketed to the aluminum industry on an as-available basis.

Pool and tailwater fluctuations are of major concern to recreation and navigation interests. Simulation tests of future peaking operations were conducted at Bonneville by rapidly changing the discharge rate and measuring the rates of change in the pool level and in downstream channel stages. Recreation interests are applying increasing pressure on operations of existing projects but are not presently concerned about operation of those in the planning stage.

PLANNING STUDIES FOR THE MINNESOTA RIVER BASIN

By

Peter A. Fischer[1]

INTRODUCTION

The reservoir system study described in this paper is a part of an overall basin study that will determine a system of improvements to meet all foreseeable short-term and long-term water and related land resource needs, not only in the Minnesota River basin, but also on the Mississippi River at and some distance below St. Paul. The reservoir study will evaluate a proposed system of multipurpose reservoirs and related channel improvements to meet primarily the needs of flood control, water quality control (low flow augmentation) and water-based recreation in the lower Minnesota River valley and the Mississippi River valley in the Minneapolis-St. Paul metropolitan area. However, flood control benefits will be evaluated on the Mississippi River to Guttenberg, Iowa, about 225 miles downstream from St. Paul. The reservoir system analysis will determine the optimum combination of reservoirs when evaluated by hydrologic and economic criteria.

DESCRIPTION OF SYSTEM

River Basin. The watershed includes an area of 16,920 square miles, of which 14,910 are in South-central Minnesota, 1,640 square miles are in Eastern South Dakota and 370 square miles are in North-central Iowa. The source of the Minnesota River is in Big Stone Lake located on the West-central border of Minnesota. From the outlet of that lake (Minnesota River mile 330.2) the river flows diagonally across Minnesota in a southeast direction to Mankato (mile 106.4), where it flows almost due north for 30 miles, then northeast for 76 miles to its confluence with the Mississippi River at St. Paul. Of the total watershed area, 14,900 square miles are above Mankato and 6,180 square miles are above Montevideo. A basin map is shown on plate 1.

The main stem meanders widely in a valley ranging from three-quarters to one mile in width and from 100 to 200 feet deep. The valley was formed in postglacial time when the glacial River Warren served as an outlet for glacial Lake Agassiz. The main tributaries and their drainage areas are shown in table 1. Tributaries entering from the west and south have similar characteristics, including steep headwater gradients flat central reaches and steep gradients in the lower reaches. Remaining tributaries generally have flat gradients and are sluggish except for their downstream steeper reaches entering the mainstem valley.

[1]Chief, Hydraulics Branch, St. Paul District

TABLE 1

MINNESOTA RIVER BASIN - DRAINAGE AREAS

Tributary River	Mainstem Location	Drainage Area in Square Miles On Tribuatary	Total on Main Stem
Little Minnesota		460	
Whetstone		400	
Yellow Bank		410	
Pomme de terre		918	
Lac qui Parle		1,110	
Chippewa		2,050	
	Montevideo		6,180
Yellow Medicine		660	
Hawk Creek		510	
Redwood		743	
	New Ulm		9,530
Cottonwood		1,295	
Little Cottonwood		234	
Blue Earth		3,550	
	Mankato		14,900
Rush		390	
High Island Creek		250	
	Carver		16,200
Sand Creek		275	
	Mouth		16,920

The topography in the basin is typical of continental glaciation being characterized by gently rolling hills separated by level outwash plains. Drainage patterns are generally well developed, except in the Chippewa basin, which has a high percentage of lakes and swamps. Soils over the entire basin are fairly uniform and consist of clay, sand and gravel or mixed loam with a heavy clay subsoil. Several areas have granite bed-rock outcrops. Soil erosion and sediment transport averages about 0.15 to 0.2 acre feet per square mile per year in the Blue Earth basin and diminishes in the Western and Northern areas of the basin.

Temperatures in the basin average about 44° F, with extremes from -42° F to about 114° F. Average annual rainfall is about 25 inches, with extremes of about 42 inches and 11 inches. Plate 2 shows the average annual runoff of the basin.

The unusual runoff characteristics of the basin produce peak flood and low flow yield potential in the 3,550-square-mile Blue Earth basin that are approximately equal to that of the entire 9,500-square-mile basin above New Ulm. Because of winter ice conditions, once release

rates are set in the fall, serious ice jams can occur if the flow is increased during the ice-cover period. Flows can normally be decreased slightly without causing problems, but they cannot be increased significantly. Therefore, a large volume of storage cannot be dumped in spring prior to runoff until after ice is well broken or weakened.

Reservoir System Under Study. Preliminary studies identified 17 potential reservoir sites in the basin, varying in capacity from 100,000 acre-feet to about 1,900,000 acre-feet. The phase I survey scope study reduced the number of reservoirs for current consideration to seven. The reservoir system analysis will investigate the optimum of alternative combinations and sizes at five sites plus downstream channel improvements or floodway easements. Plate 3 shows the location and potential ultimate capacities of these five reservoirs.

OBJECTIVES OF THE SYSTEM ANALYSIS

The objective of the system analysis of reservoir operation is to determine the optimum combination of reservoir sites, capacities, operating plans and floodway capacity to maximize benefits for flood control, quality control and recreation when evaluated by economic and hydrologic criteria. Severe flood problems exist in urban and agricultural areas along the Minnesota River from Mankato to the mouth and along the Mississippi River downstream from St. Paul. Alleviation of these problems will produce about 65 percent of the total project benefits. Approximately 65 percent of the flood control benefits have been identified at Mankato, the lower Minnesota River downstream from Carver and in the metropolitan Minneapolis-St. Paul area. Approximately 13 percent of the flood control benefit will accrue on the Mississippi River downstream from the mouth of the St. Croix River. Current and future water quality problems will produce about 18 percent of the total benefits and have been identified at Mankato, the Minnesota River reach downstream from Chaska and downstream from the Minneapolis-St. Paul Sanitary District Treatment Plant in St. Paul. Demands for water-based recreation exist in the Mankato area and in the Minneapolis-St. Paul metropolitan area.

CURRENT STATUS OF PLANNING

As mentioned, the phase I studies have been completed. Detailed flood control studies using approximate methods based primarily on relating modified frequency curves to percentage of drainage area controlled have been initiated for the Blue Earth, New Ulm, Cottonwood and Carver sites acting singly and in combination. Studies for quality control using a storage-yield-probability analysis have also been started for both the Blue Earth and New Ulm reservoirs. An interim report on the Blue Earth reservoir as a single, multipurpose, first-in-place unit in the system will be completed in the near future.

Controlled drainage area-frequency relationships and storage-yield-probability analyses do not adequately define operational alternatives, timing and syncronization of discharge, nor variations in areal distribution of runoff for any flood or low flow period. Therefore, these approximate methods of analysis were found to be inadequate for detailed analysis of the single units of the system and they were found to be totally unsuitable for an analysis of a multiple-unit system.

Detailed reservoir operation studies of historical or simulated discharge sequences on a system-wide basis will more adequately define required reservoir combinations, sizes and operating plans. Consequently, arrangements were made with The Hydrologic Engineering Center for assistance in problem definition, determination of suitable methods including modifications to and use of the generalized computer program HEC-3 "Reservoir System Analysis", and performing the detailed system analysis. The remainder of this paper will summarize the techniques that will be used in the detailed system analysis of the five Minnesota River basin reservoirs, with discussion of problem areas and needs for improved methods.

METHODS ADOPTED FOR MINNESOTA RIVER RESERVOIR SYSTEM ANALYSIS

Basically, the methods which will be used for the reservoir system analysis will be those incorporated into the HEC generalized computer program HEC-3, "Reservoir System Analysis" but modified to incorporate routines necessary for flood control studies. The program as now written is primarily developed for power, irrigation or other long-interval studies not greatly influenced by short-duration transients such as flood peaks.

Description of Basic HEC-3. The following brief description of HEC-3 was summarized and is quoted in part from the generalized computer program writeup published by HEC in December 1968. The program writeup or HEC staff members should be consulted to obtain a complete program description, including modifications incorporated into the current program. The program, written in Fortran IV, will perform a multi-purpose, multireservoir routing analysis of a reservoir system. Any number of monthly periods of uniform or varying length per year are routed based on established flow requirements at the reservoirs, diversions and downstream control points. Reservoir release rates are also determined by the established power requirement at each reservoir. The program will accept any system configuration and will accept system power demands that over-ride individual power plant requirements; however, the program does not automatically provide for channel routings, percolation losses, time translations or other attenuation effects of channel phase flow. The program can assign economic values to outputs and summarize and allocate these in various ways.

The program can establish release rates that will maintain a specified balance of storage in all reservoirs depending upon system yield capabilities defined by the system input hydrographs. Based on a defined set of reservoir levels, releases from storage can be adjusted automatically to a reduced secondary flow at each downstream control point until active storage is depleted in the system. A routine is also included to declare shortages and thus reduce desired flows and diversions covering a period less than 1 year. The shortage declaration is based on total storage at the beginning of a specified period at specified reservoirs and is proportional to total storage deficiency in these reservoirs at the beginning of the period. Basin development, operation plans or demand schedules can be altered at the ends of designated years within the total period of record being studied.

The program as now written is not intended for short-interval flood study but will provide maximum releases subject to downstream controls whenever there is water in the flood control space at a reservoir. The program will not currently permit surcharge storage operation and will spill all water above full reservoir level. Reservoir release rates can be automatically adjusted based on a function of local inflow above each control point downstream of reservoirs to provide a contingency allowance for both flood control and water supply. Diversions into and out of the stream must be either specified as fixed amounts for each period or identified as a ratio of any previously computed diversion for that period. Net evaporation can be deducted as different annual totals but using the same seasonal distribution for all reservoirs.

Proposed Program Modifications. Because the program will be used in the plan formulation stage of analysis and since flood control will contribute the majority of benefits, the existing program will be modified to include the capability of short-interval flood control routing and an integration of total benefits for each operating plan or reservoir system configuration analyzed. Modifications to the program will be developed by Mr. Beard and the HEC staff over the next 4 months with completion in February 1970, if all goes well. A routine will be developed to permit surcharge flood control storage in reservoirs above full pool level. The release rates will be based on an elevation discharge curve computed from the geometric characteristics of the spillways and outlet works and surcharge operating plans; however, surcharge operation at a reservoir will be determined from only one unique rating curve for each reservoir in a given system or operating plan being analyzed. Surcharge release rates based upon a function of inflow will not be used.

The second change proposed for HEC-3 will permit the routing of short-interval, either daily or 12-hour average, flows to reflect the influence of the reservoirs on reducing downstream flood peaks. Since floods may occur during different seasons of the year, provisions will be included to permit starting with different storage levels in the reservoirs for the different seasons. The floods will be routed to downstream control points using a simple time translation technique only, with no provisions

in the program for the attenuation affects of channel storage and other channel phase flow phenomena. No provisions will be included for the backwater or temporary storage conditions at the confluence of a tributary with the mainstem. Although these deficiencies in the program may introduce some significant routing errors when determining modified downstream flood peaks, the program will be used primarily for project formulation of the optimum reservoir system, and results for each system studied should be accurate relative to each other for comparison purposes. Modified discharges determined from HEC-3 will be compared with results using HEC-1 "Flood Hydrograph Package" or other refined routing techniques to determine the degree of variation experienced, relative accuracy of HEC-3 and actual modified peaks to be expected from the adopted optimum system.

A flood iteration routine will be incorporated into the program to permit the routing of each daily or 12-hour average flow through the system and then construct and store in memory the entire modified hydrograph at each downstream control point. The iteration routine will permit the routing of a number of different historical or artificially constructed floods through the system and then compare project peaks with pre-project peaks at each control point to determine effect of project operation.

The program modification that will compute modified frequency curves will develop a curve or mathematical function relating project to pre-project flows developed from the flood routing and iteration routines. This function and the pre-project frequency curve will be used to establish the modified project curve at each control point. At control points immediately downstream from a major uncontrolled tributary, the maximum allowable shift in modified frequency curve may be limited by the frequency curve of the uncontrolled tributary. It may be necessary to incorporate a procedure into the program which will prevent the modified frequency curve from falling below the controlling curve of the upstream tributary.

Discharge-damage curves at each control point plus the pre-project and project discharge-frequency curves will be used in a new routine to compute benefits at each point. The routine will compute total benefits at each point and will accumulate benefits from each point along the stream to determine total benefits for the plan being analyzed. Reservoir costs and channel-improvement costs will also be summarized for each system. Low-flow regulation and recreation studies will be accomplished by using an essentially unmodified version of HEC-3 for routing the historical monthly runoff through each proposed system. Low-flow and recreation benefits will be identified, tabulated and summarized at each reservoir and control point for each system analyzed.

Input Data to System Analysis. A summary of input data that will be required for the modified program for reservoir system analysis will help identify the capabilities of the program and its use in the Minnesota River basin studies. Input tables will include the physical characteristics of the reservoirs including elevation-storage-area data, reservoir elevation-cost data, spillway rating curves, outlet works capacity and critical or priority storage levels in acre-feet at each reservoir for each period of the year. These levels will include minimum spring pool level, summer operating levels, top of any buffer zones or intermediate dedicated water quality storage zones, desirable summer recreation levels, full flood pool and other critical levels. Power plants are described by fixed values of tailwater elevation, nameplate and overload capacity. Power plant efficiency is also included as a fixed value or in tabular form related to storage or head. Basin configuration is included schematically to locate relative position of the three mainstem reservoirs and two tributary reservoirs with the approximately 29 control or damage points and the various points where inflow hydrographs are developed. Travel times for flood flows and low flows between each reservoir and control point are also included. The controlling high-flow channel capacity and low-flow demand rate at each control point for each season will be used to determine controlled release rates from each reservoir. Also, a relationship of channel capacity to improvement (or acquisition) cost will be used to determine costs of increasing the non-damage capacity.

Monthly streamflow into each reservoir and at each uncontrolled tributary and factors to be used to interpolate required local inflows where needed will be used in the low-flow and recreation studies. Short-interval flood hydrographs at each reservoir and tributary and factors for selecting missing local inflow hydrographs will be used in the flood control studies. Because of the variety of recorded flood types, flood magnitudes and sources of runoff, a variety of flood patterns will be used in evaluating reservoir effects. Accordingly, the 10 largest floods that have occurred during about the past 50 years will be selected on the basis of peak flow at St. Paul and total volume at Mankato. In order to obtain flood magnitudes in the upper range of the flood frequency curves, each flood at Mankato will be multiplied by a factor of two. The use of these augmented floods and the 10 as observed will thus provide a total of 20 floods for study. The multiplier for downstream and tributary hydrographs will be determined by analysis of discharge frequency curves at downstream points to obtain flood data that is consistent and comparable to the frequency curves along the river.

Discharge-damage and discharge-frequency data for each of the 29 damage reaches related to the 29 control points will be used to evaluate benefits of each system analyzed for flood benefits. The reservoir and channel cost data will be used to determine the excess of benefits over

costs for each system studied. Discharge-benefit data will also be used at those control points included in the low-flow and recreation analysis. Also, a curve of elevation versus recreation benefits will be supplied for each reservoir.

Seasonal operation schedules for each reservoir system to be analyzed will be incorporated into the rating curve data, critical storage levels and downstream channel capacities or demand rates.

Use of Program in System Analysis. In actual use during the system optimization and formulation process, the program will analyze, first, various flood control systems on a trial-and-error basis, evaluating for each system the total benefits versus reservoir and downstream channel improvement costs to determine which system is optimum based on flood control benefits. This system will then be analyzed to include various levels of water quality and recreation development. Inasmuch as the flood studies require short-interval analysis for flood periods only and low-flow and recreation studies must be done on a monthly basis for a continuous long period, the two studies will be analyzed separately, but on a coordinated basis using HEC-3. It is anticipated that the program de-bugging and preliminary flood and low-flow studies will be finished by the end of June 1970. Detailed studies for system optimization will then be undertaken in the following one to two years.

PROBLEMS ENCOUNTERED AND NEEDS FOR FUTURE DEVELOPMENT

Although Minnesota River system analysis studies are only starting, certain problems have emerged which will require detailed examination and development of improved methods.

Channel routing routines in HEC-3 are limited to a time translation process only. Addition of refined channel routing techniques would substantially improve accuracy of results, particularly when the program is used in a system with a channel having substantial attenuation effects on flood peaks.

Additional study is needed in developing a reliable method to determine modified frequency curves from analysis of pre-project and modified hydrographs of either historical flood events or synthetic balanced flood hydrographs of specified frequency. The new technique being added to HEC-3 should help in this area.

Improvements in the examination of characteristic historical flood and low-flow events is needed to improve reliability in determining the capabilities of a system of reservoirs. Extreme flood and drought events in a historical record that may not be typical of the period of record may lead to unrealistic estimates of the degree of protection provided by the system.

The current methods of monthly flow simulation used by HEC on the Minnesota River historical discharge records produced results that were slightly inconsistent. When simulating a sequence of low-flow periods, the summation of discharges from upstream tributaries significantly exceeded the flow at the downstream mainstem station. Further development in techniques for both monthly and daily flow simulation is needed.

The formulation and optimization process would be improved if a computer program would simultaneously integrate both flood flow and low flow studies based on efficiency criteria specified as input data. It should be the ultimate goal when developing a system analysis program to produce one that would automatically optimize the system based on predetermined constraints and efficiency criteria.

When HEC-3 is used for flow augmentation analysis, a technique should be incorporated that would discount recreation benefits based on a relationship of benefits reductions versus seasonal pool fluctuation. The program should determine the total reservoir fluctuation in the season and then discount the recreation benefits for the particular reservoir stage based on this fluctuation. Although detailed system analysis studies are just starting on the Minnesota River study, it is apparent that the use of HEC-3 with planned modifications will greatly improve the reservoir formulation and optimization process; however, even at this early stage in the study, several areas for future program and methods development have been identified.

SUMMARY OF DISCUSSION

Compiled by R. L. Cooley[1]

There was a question as to why runoff is only 1 inch in a part of the basin even though there is about 25 inches of average annual precipitation. Slopes are relatively flat in the area and much of the precipitation infiltrates. Also, the even distribution of rainfall combined with flat slopes tends to produce a high evapotranspiration rate. The proportion of runoff to rainfall is highest in the spring when the winter's snow is melting, when as much as 80 to 90 percent of the water equivalent of the snow may become runoff.

A problem in reservoir operation in the basin arises because the winter release rates must be committed in the fall before the rivers are covered with ice. Because of the ice cover, no opportunity is available to make major adjustments in release rates should the forecast indicate the desirability for change during the winter. One of the members of the group commented that the discharges can be progressively increased, because the under surface of the ice and possibly the bed are smoothed, permitting the higher releases. This would possibly be effective if started in early winter when the ice cover was thin.

There was a question as to what progress has been made in the planned program modifications to HEC 3. Mr. Beard commented that most of the changes in HEC 3 for short-term routing have been coded but are, as yet, untested. The program takes into account time translation effects but will not be modified to include attenuation effects. The program HEC 1 takes these effects into account, but, because of the structure of HEC 3, modification to include attenuation effects would be very difficult, if not impossible.

Design of authorized levee projects in the Minnesota River Basin has been complicated by the reservoir studies, because the reservoirs will affect the required height of levees. This evaluation is complicated by the fact that heavy summer rains would produce the standard project flood for small drainage areas, but for larger areas, snowmelt combined with rainfall would produce the standard project flood. The interim report on the Blue Earth Reservoir will help to define design levee heights for the local flood protection projects.

The April flood of 1969 provided some reliable benefit figures for flood damages. Temporary levees erected under Operation Foresight for this flood helped prevent major flood damages. However, in general, early and reliable forecasts cannot be counted upon to permit an Operation Foresight type of response.

[1] Hydrologist, Ground Water Branch, The Hydrologic Engineering Center

It was pointed out that substantial fluctuations in stage during the recreation season will reduce the recreation benefits. Routines to evaluate recreation benefits should include a discount function related to pool fluctuation during the recreation season.

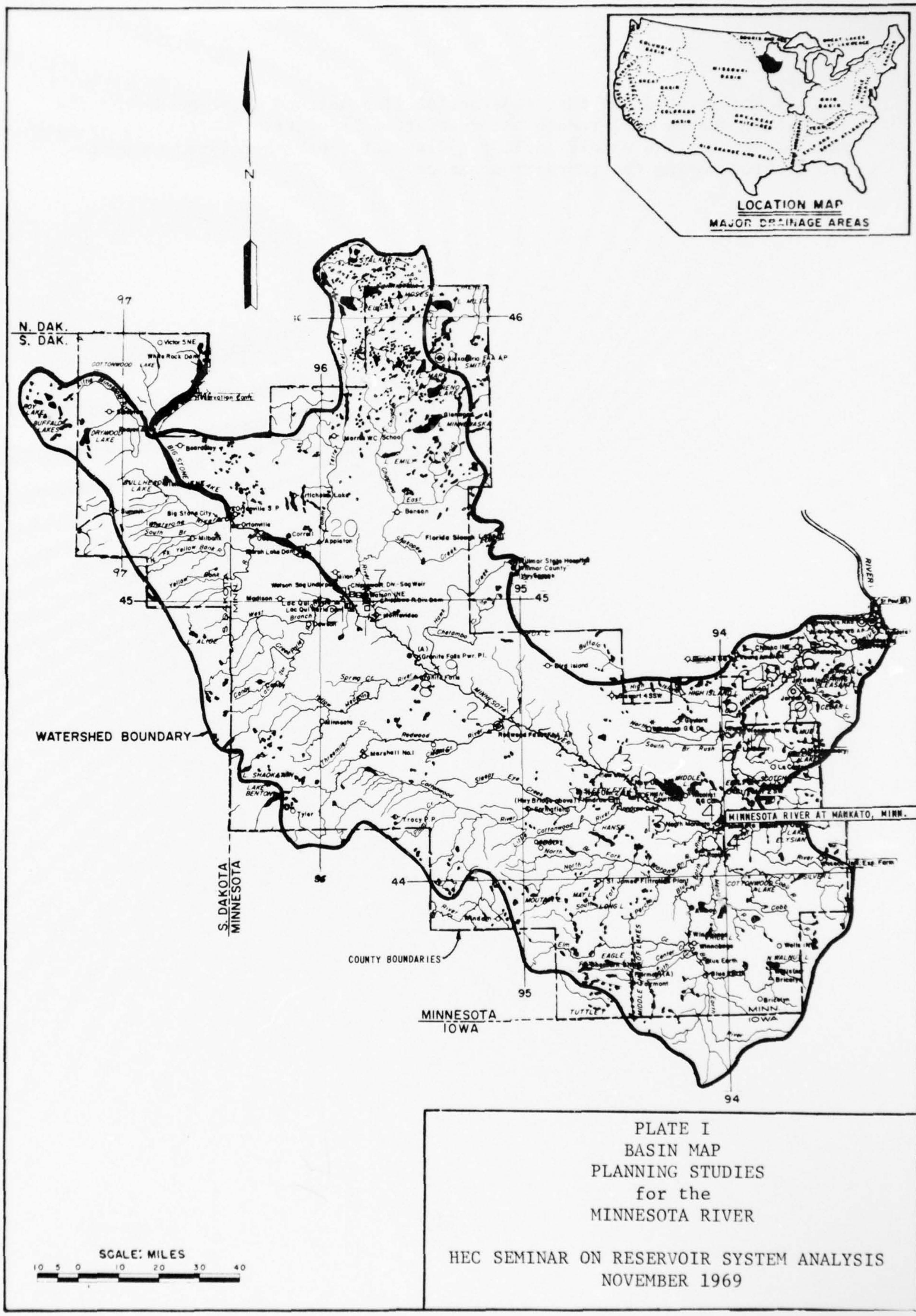

PLATE I
BASIN MAP
PLANNING STUDIES
for the
MINNESOTA RIVER

HEC SEMINAR ON RESERVOIR SYSTEM ANALYSIS
NOVEMBER 1969

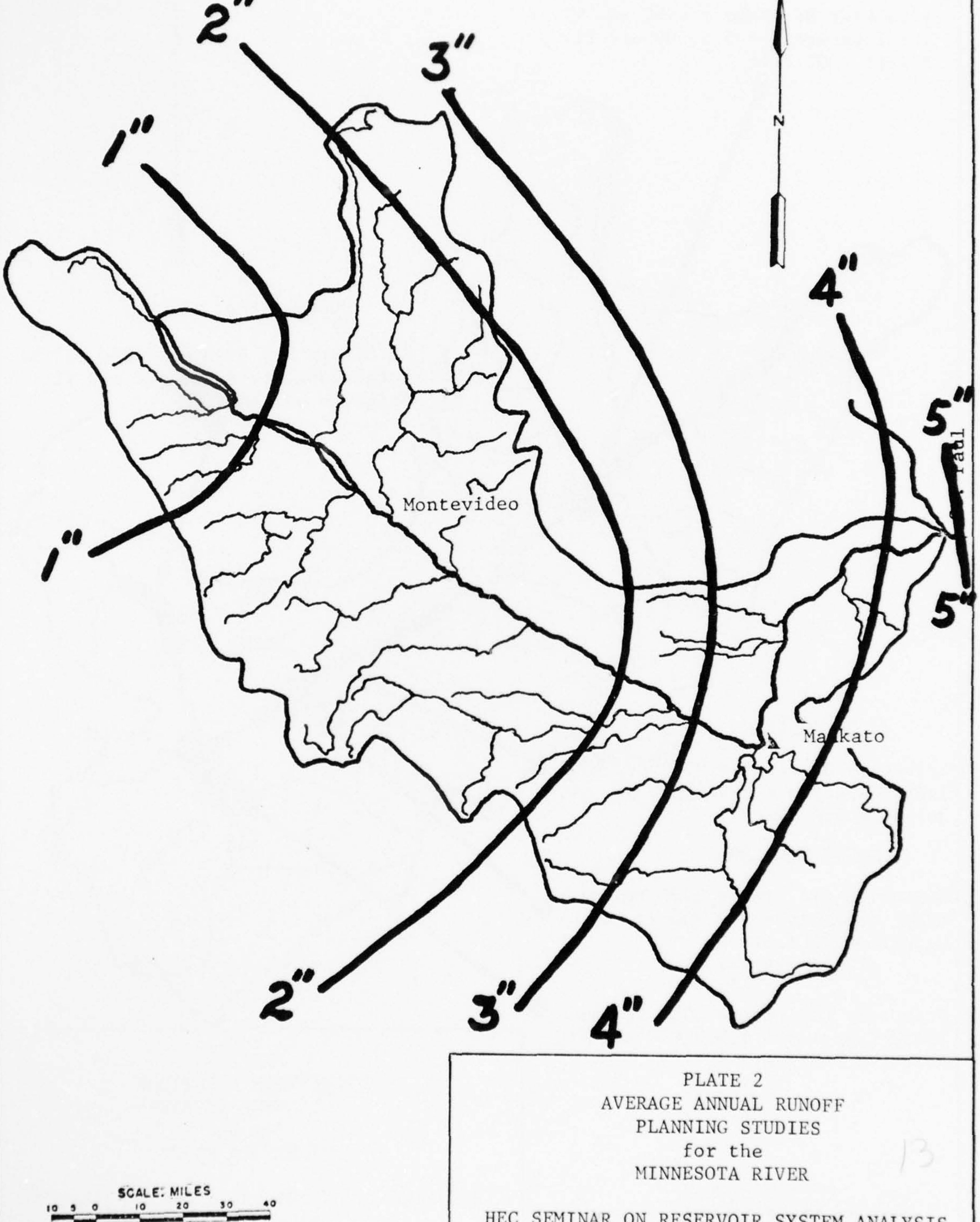

PLATE 2
AVERAGE ANNUAL RUNOFF
PLANNING STUDIES
for the
MINNESOTA RIVER

HEC SEMINAR ON RESERVOIR SYSTEM ANALYSIS
NOVEMBER 1969

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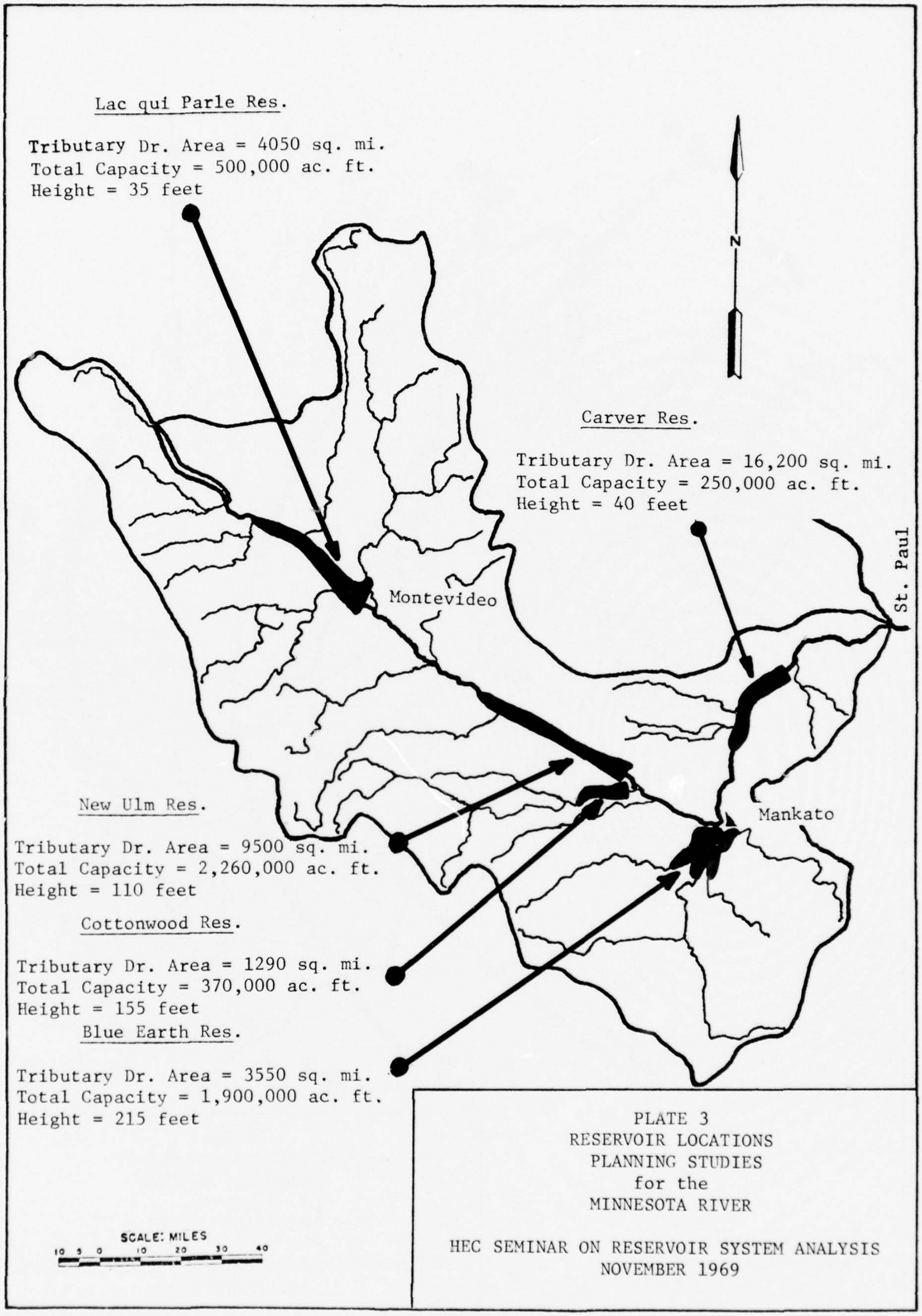


PLATE 3
RESERVOIR LOCATIONS
PLANNING STUDIES
for the
MINNESOTA RIVER

HEC SEMINAR ON RESERVOIR SYSTEM ANALYSIS
NOVEMBER 1969

ARKANSAS-WHITE-RED RIVERS
RESERVOIR SYSTEM CONSERVATION STUDIES

By

C. Pat Davis[1]

This paper describes a study under way for a business with an 88 million dollar-a-year income. It focuses primarily on the hydropower division which accounts for 42 of the 88 million dollars. This business consists of a multi-purpose reservoir system located in Oklahoma, Arkansas, Texas, Kansas, New Mexico, Missouri and Colorado. Its Board of Directors is the Southwestern Division (SWD) and Little Rock (LRD) and Tulsa Districts (TD), Corps of Engineers.

Now for a brief description of the area. The drainage area of the three basins extends from the headwaters of the Arkansas River near Leadville, Colorado, at the continental divide east-south-eastward to near the mouth of the Mississippi River where the Red River empties into that stream. A map of Arkansas-White-Red River Basins and the reservoirs is shown on plate 1. The Red River is shown only to the Southwestern Division boundary which is all the area that will be considered at this time.

The Arkansas-White-Red rivers and their tributaries drain approximately one-eleventh of the nation's conterminous land area. The A-W-R area considered in these studies is within the Southwestern Division, consisting of about 233,000 square miles with the Arkansas draining 159,000 square miles; the White 22,000; and the Red 52,000. The principal surface features of the A-W-R Basins are a relatively small extent of high mountains in the west, a large area of low mountains which rise abruptly from the Coastal and Mississippi Alluvial Plains in the east and a broad expanse of interior lowland.

Annual precipitation averages about 50 inches over most of Arkansas. It decreases rather uniformly westward to about 16 inches in western Oklahoma, then increases to 32 inches in the mountains of Colorado and New Mexico. Annual runoff is even more varied with up to 25 inches in southeast Arkansas and almost zero for many of the areas in the western Great Plains. The eastern half of the Arkansas-White-Red (A-W-R) area contributes 95 percent of the annual runoff.

The period of high runoff starts in the winter and early spring in the southeast area and moves northwestward rather uniformly in time to late spring and summer in the Great Plains areas. During the extended droughts that are characteristic of the western half of the Basins, only major rivers maintain continuous flows. In the humid eastern lowlands, recurring floods frequently spread waters over wide expanses of adjacent lowlands.

[1]Hydraulic Engineer, Reservoir Control Center, Southwestern Division

This business began almost thirty years ago with one reservoir, operated for power and flood control, and has grown to over forty reservoirs operated for at least seven purposes. The investment has grown from 30 million to more than 2 billion dollars. This accounts for all the Corps projects in the basins including the Arkansas Navigation Projects. The investment of the 25 reservoirs included in this study is 1.5 billion dollars. And like many businesses, the projects have been added as you would add rooms to a house until the original architecture is no longer apparent. For example, all the power projects were designed as peaking plants. They were designed individually or in some cases as two or three reservoir systems to stand alone in meeting peak power demands during the worst drought of record. The marketing agency, Southwestern Power Administration (SPA), has constracted for thermal power, so the projects now form a system with both Corps hydro and private thermal integrated.

How can this business be brought into 1969 prospective? Should it operate for recreation, even though recreation is not an authorized purpose? And if it is, how should the operation be modified in the interest of recreation? How should the individual power plants be best integrated into a power system? Can encroachment be made on the flood control pool at certain seasons inorder to improve over-all accomplishments? It is recognized that the objective should be to determine the best operation for all project purposes using an appropriate base, subject to authorization, legal and social constraints. At the same time the "state of the art" may require something less.

METHOD OF ATTACK

The Southwestern Division and its District Offices have chosen to concentrate on the purposes that can readily be improved while maintaining at least equal benefits for other purposes. However, the over-all objective is kept in mind. To be more specific, the immediate objective of this study is to establish better hydropower operating criteria while adhering to present designs for water quality, water supply and navigation and flood control. Average annual flood control and recreation benefits would not be decreased. However, a seasonal variation in the top of conservation pool might re-arrange the flood control and recreation benefits within the year. It might be well to repeat Webster's definition of criterion which is: "A standard on which a judgment or decision may be based." Standards are expected to be developed from this study upon which to base the decisions to purchase energy or to generate secondary energy. Of course, the criteria developed will have to be tempered with current information such as the present price of energy. These decisions must be made with cooperation between the Corps and SPA. The effects of various operations on flood control and recreation will also be determined.

SYSTEM DESCRIPTION

There are twenty-five projects included in this study - twenty-two Corps projects and three non-federal projects. Six of the Corps projects are under construction and will be completed between now and 1973. Of the sixteen now in operation twelve include hydropower with a combined generation capacity of 1351 megawatts. There will be four additional hydropower projects bringing the total installed capacity to 1652 megawatts. All of the additional hydropower projects are in the Arkansas River Basin. When completed there will be two projects with 170 megawatts installed capacity in the Red River Basin, nine with 664 megawatts in the Arkansas and five with 818 megawatts in the White. Two of the non-federal projects are in the Arkansas River Basin with 187 megawatts and one with 16 megawatts capacity is located in the White River Basin. The total Corps system has an approximate minimum year energy of 1700 gigawatt (1000-megawatt) hours, which corresponds to 12 percent load factor. Average annual energy is 5,000 gigawatt hours, corresponding to a 34-percent load factor. These values are based on previous studies and probably will change with this study. The system load is about 80 percent of the average annual hydro or 4000 gigawatt hours. The load is met by hydro purchases of thermal energy in below-average water years. In fact, it may be necessary to purchase energy even in an average water year if the inflow is not well distributed, since the projects can store enough energy to meet the load for only a few months.

Plate 2 shows a schematic of the system and plate 3 shows some pertinent data of the projects. The usable conservation storage of the projects ranges from "run-of-river" which have only a small amount of regulating storage to projects with 1,500,000 acre-feet of conservation storage. Power heads range from as low as 28 feet for the Arkansas River navigation projects to 200 feet for the White River projects. This system is complicated not only because it consists of three basins but also because there are two power systems. Table Rock and Bull Shoals comprise one system while the other projects comprise another.

STUDY

System studies have been discussed many times - especially when talking about the A-W-R hydropower network. Although subsystems have been analyzed, no total system study has been made by the Corps, principally because of manpower shortages and lack of computer capability. The establishment of the Reservoir Control Center increased the manpower in SWD, and it now can coordinate the study with Tulsa and Little Rock Districts. A computer routing program and machine capability to handle such a program are now available.

This study began in August 1967. Representatives of Tulsa, Little Rock and Forth Worth Districts were called to a meeting in Dallas. The purpose of the conference was to discuss and ititiate studies needed to optimize project benefits. Of course, there was an inkling of the magnitude of this type of study. To optimize numerous functions which have no common denominator has perplexed many water resource managers. We wished for a "classic" computer program which would analyze all functions with one pass. It must be economical and print out the answer in 25 words or less. After some discussion it was concluded that this just might take a little time to develop. Because of the magnitude of benefits for the projects that include power, it was decided to concentrate on these projects first. A committee was appointed to draft a work plan, and this was completed in September 1967. The objective was to develop reservoir regulation procedures that would obtain optimum beneficial use of the power projects, considering all authorized and approved purposes. It was realized that there were limitations on what could be done with existing District computer programs and computer capability. For example, there was no comprehensive program which would analyze both flood control and power. Even a program to analyze the total system for power was not available; therefore, the group anticipated analyzing the three basins separately then integrating them into a system.

NEED FOR ASSISTANCE

Between September 1967 and October 1968 several meetings were held. Some seasonal variation in the top of conservation pools was initiated at four projects, and a hydropower report for the White River project was submitted to SWD. Although work on the total system had not been forgotten, little had been accomplished. The slow pace was mainly due to heavy workload and lack of manpower. It became evident that something must be done to speed the study if a reasonable schedule was to be maintained. In July of 1968 members of the Reservoir Control Center at SWD and The Hydrologic Engineering Center (HEC) discussed the study in general and particularly the use of the Reservoir System Analysis Program developed by HEC.

Several papers have been written on the Reservoir System program and a copy of its documentation can be obtained from The Hydrologic Engineering Center; however, a very brief description will be given here. This program performs multi-reservoir routings of one of several reservoir systems by any number of periods of uniform or varying length per year based on flow requirements at reservoirs, diversions, and downstream control points and power requirements at reservoirs. It will accept system power demands that over-ride individual power plant requirements. It can assign economic values to reservoir functions and summarize and allocate these in various ways. All requirements are supplied from reservoirs so as to maintain a specified balance of storage in all reservoirs, insofar as

possible. At reservoir stages below specified levels, releases from storage at each reservoir are reduced to a secondary specified requirement at each control point until all active storage is withdrawn. Provision is included for shortage declaration during dry years which will reduce desired flows and diversions covering a period less than one year. The program is not intended for short interval flood study, but will restrict maximum releases to downstream controls whenever there is water in the flood control space at a reservoir and will not store above full reservoir level. This program was prepared for use in the CDC 6600 computer but is usable on other high speed computers if dimensions are changed to fit memory size. The program permits specification of one or more power systems wherein the overall required generation exceeds the sum of required generation at the individual plants within the system. The difference is automatically assigned to plants in such a way as to keep reservoir storages most nearly in balance, subject to other system requirements and maximum system load factor.

It was found that HEC could probably assist with both manpower and computer capability. The desirability and feasibility of using the HEC program was discussed in October 1968 at a meeting attended by Forth Worth, Tulsa and Little Rock Districts. It was confirmed that considerable time and manpower would be required for the Districts to modify their existing programs to route sub-systems for the period of record. It was then agreed to use the HEC developed program. On 26 November 1968 a conference was held between the Districts, SWD and HEC to discuss HEC's assistance and the program. Some program changes were made to enlarge its capability to handle the A-W-R system and available data. HEC was anxious to help with the study because of the complexity and the potential for developing additional methods and techniques of system analysis.

A satisfactory run of the program was made the first week in May. The first run was primarily to verify the data and the program logic and to establish the methods needed to analyze the output. No specific operating rules were applied except that the flood control pool would be evacuated as rapidly as downstream conditions would permit. The projects were operated to maintain, as nearly as the constraints would permit, equal balance of remaining conservation storage. The systems' driest period was determined. It was found that there was some 10 percent (or 200 gigawatt hours) diversity between the basins. That is, the minimum annual energy would be 10 percent more when the three basins were operated as one system instead of three systems. A meeting was then held in July 1969 to discuss progress of study and to plan the next work. The study had progressed to a point where coordination with the Southwestern Power Administration was needed. They were asked to participate in the study and attended this meeting.

IMMEDIATE PLANS

Plate 4 shows an illustration of operating curves for the system. Possible additional curves would be needed for some or all individual projects. The chart is based on a combined hydro and thermal power system which has a load larger than could be supplied by hydro during a dry period. Consequently, some thermal energy must be purchased, but when and how much must be determined. Curves such as those illustrated will merely give guidance for decisions, and will not eliminate the necessity of making decisions based on current information. Area "D" would be delineated so that the load could be met, using all available hydro and thermal resources, under the most adverse conditions. Areas "A" "B" and "C" would be delineated by considerations of economic factors, rather than to guard against extreme drought conditions. Economic factors would include such features as keeping the head high to obtain more energy from a given flow, without unduly increasing spill. The seasonal variation in cost of thermal energy will influence the operation curves. The procedure for determining the operation curves would consist of consecutive trial runs and modifying the curves on the basis of detailed analysis of the system operation.

It is clear that the study must be a combined effort between the Corps and the Southwestern Power Administration. The Southwestern Power Administration will furnish the load data necessary to determine the boundaries of the areas. Such data will include the total load to be met and the minimum amount of hydro that can be tolerated and the annual distribution of these loads. This will also be a procedure of successive approximations, since minimum hydro will not be known until the characteristics of the hydro resources are compared with the total load resources. The Corps will furnish the hydro characteristic to the SPA who will make this comparison and revise or confirm the previous data.

NEEDS

There are several urgent needs. Most of these apply not only to this study but to practically all such system studies. One need is an efficient way to analyze the mass or printout for each run. The Little Rock District has magnetic tapes of the printout and is experimenting with processing the information. Some of the information has merely been rearranged and some has been plotted. The Southwestern Division is also funding some research by HEC in this area. One thing that complicates this problem is the difficulty in deciding just what information is really pertinent for each run and how the pertinent information should be presented. There are several persons involved in this study and as a result there are several ideas on what information is important. Two types of analyses are required. One of each run in order to change data for the next run and another type is needed to convey the information in a report.

How the simulation program will handle rule-curve operation is another area needing some research. The system operation is currently using a dummy project to represent the required purchase energy. This operation is not completely satisfactory, and The Hydrologic Engineering Center is now doing some research in this area with assistance from SWD.

There is also a need for techniques to optimize the unbalance in reservoir storage. Here again several or maybe all the project purposes may influence the balance or unbalance between reservoirs; however, even to consider only one purpose is difficult. The optimum balance is a factor of hydrologic characteristics, reservoir storage, flow requirements, turbine or outlet capacity and several other factors to a lesser degree, so it can readily be seen how difficult it is to find the most satisfactory relationship between these variables for more than a couple of reservoirs.

Other areas of concern are: Just how much error do we encounter by using monthly intervals in lieu of weekly or daily? Can or should we use a contingency factor for this? How should we analyze such purposes as flood control, which must be studied on a daily or shorter interval, in a basically conservation study? How do we evaluate affect of drawdown on recreation?

As of now there is no clear cut answer to these questions.

SUMMARY

The objective of this study is to develop better operating criteria for the Arkansas-White-Red River projects which include hydropower. These criteria will be based on an integrated analysis of hydro and thermal power. It will include the evaluation of:

- Seasonal pool levels
- Purchase of thermal energy
- Best balance of reservoirs to reduce spills and maintain a high power head
- Generation of secondary energy and operation for project purposes other than hydropower

To facilitate accomplishment of these goals some needs are:

- Better methods to analyze computer output
- Simulation of rule curve operation
- Optimization techniques
- Evaluation of drawdown of recreation

ACKNOWLEDGMENTS

This is a cooperative study between the Corps of Engineers' Southwestern Division, Little Rock and Tulsa Districts, The Hydrologic Engineering Center and the Southwestern Power Administration. There are many persons in these offices that have helped me broaden my knowledge of system studies and in various ways impressed upon me the difficulty involved in making such a study as this. The Southwestern Power Administration has provided assistances for this study and has been very helpful and patient in discussing the marketing of power from these reservoirs and their system in general. Gerald Thomas of the Little Rock District, who has made subsystem studies of the White River projects and has been advocating a system study of these three basins for years, has been especially helpful. Don Henderson of the Tulsa District has also contributed much. I cannot name everyone involved; however, I must mention A.J. Fredrich of The Hydrologic Engineering Center for his effort in this study. Special thanks go to W.S. Swanson, who is the other half of the Power Production Section, and to David L. Leinbach, Chief Reservoir Control Center and F.L. Nixon, Chief, Reservoir Regulation Section for their suggestions on this paper.

SUMMARY OF DISCUSSION

Compiled by D. C. Lewis[1]

The hydroelectric power facilities of the Arkansas-White-Red River system are all interconnected electrically, partially by use of utilities' transmission facilities and partly by SPA constructed lines. The customers are primarily cooperatives who contract for power with the Southwestern Power Administration (SPA). In a few cases, SPA furnished firm power to cooperatives having no thermal power capability. The SPA markets both energy and capacity from Corps of Engineers projects. Power is only one of seven purposes served by reservoirs in the system.

The 200 GWA increased output realizable by operating the AWR projects as one system instead of three additive systems is due to the hydraulic diversity within the three basins during the critical period. The projects must be operated as one system in order to gain the benefit of the diversity. Added benefits could accrue in non-critical years.

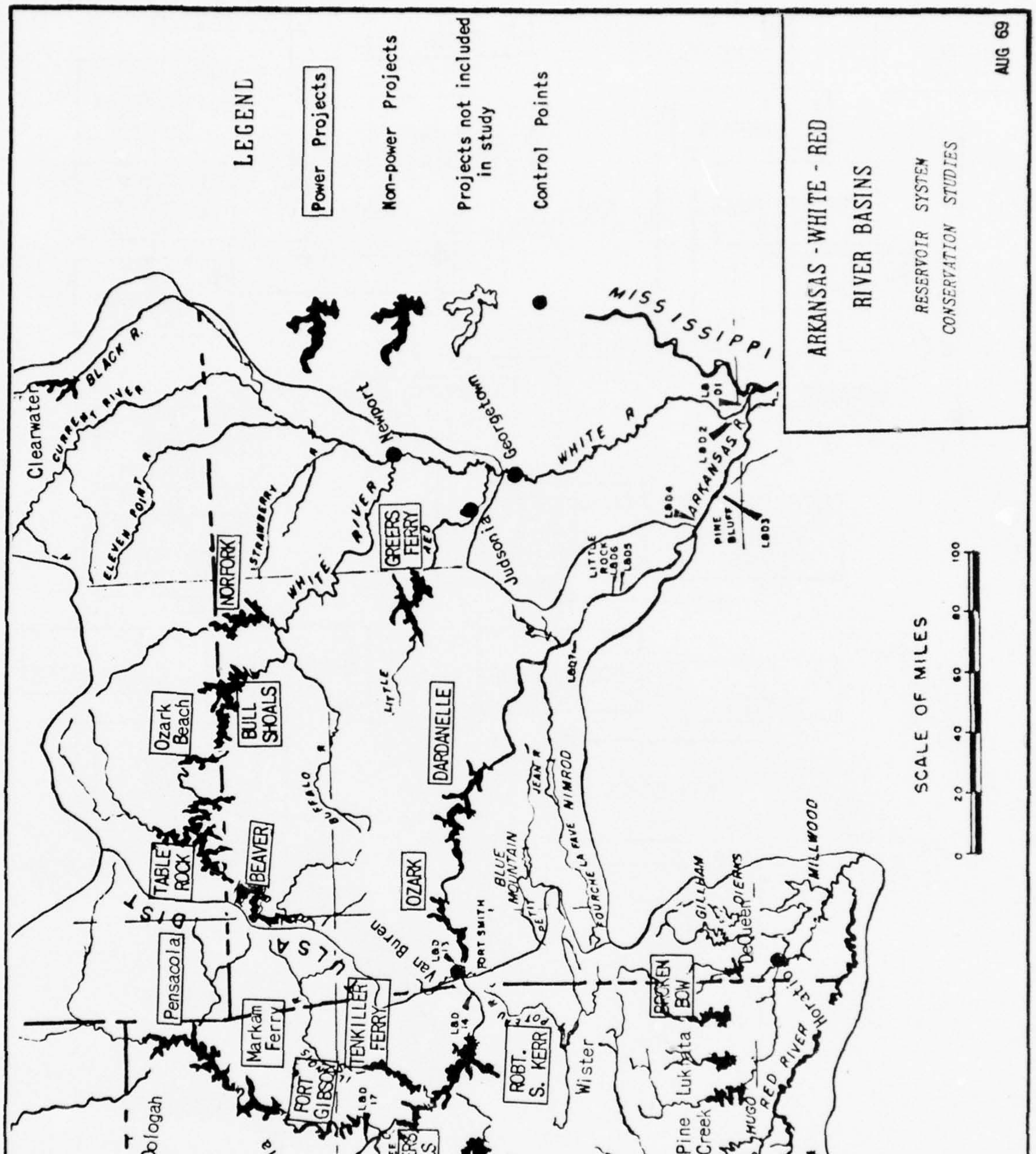
The technique of balancing storage at the same percentages of full pool for all reservoirs in the system at all times is questionable. It was pointed out that this is only a first approximation of optimum, and that hydrologic and power diversity will surely require non-proportional balancing criteria. In optimizing system operation a storage-use index can be used in choosing the best location for a given power release at a given time. This index could include consideration of relative head change at possible alternative generation sources. Such an operation usually corresponds to holding downstream reservoirs full while drawing on upstream reservoirs.

A system design based on fixed power requirements may be too rigid in terms of actual operation requirements. Power requirements are stochastic rather than fixed. The AWR system supplies power to a load that includes thermal as well as hydropower requirements, thus there are alternate ways of meeting actual requirements. In some respects the hydropower represents a constraint on overall power production, because reservoirs must also be operated for other purposes.

The complexity of the AWR system is demonstrated by the disparity in flood control operation in the different rivers. The Arkansas River has 150,000 cfs channel capacities in most reaches, which permits rapid evacuation of flood control space and secondary power generation. The White River has smaller channel capacities, and power releases may be reduced during flood control operation.

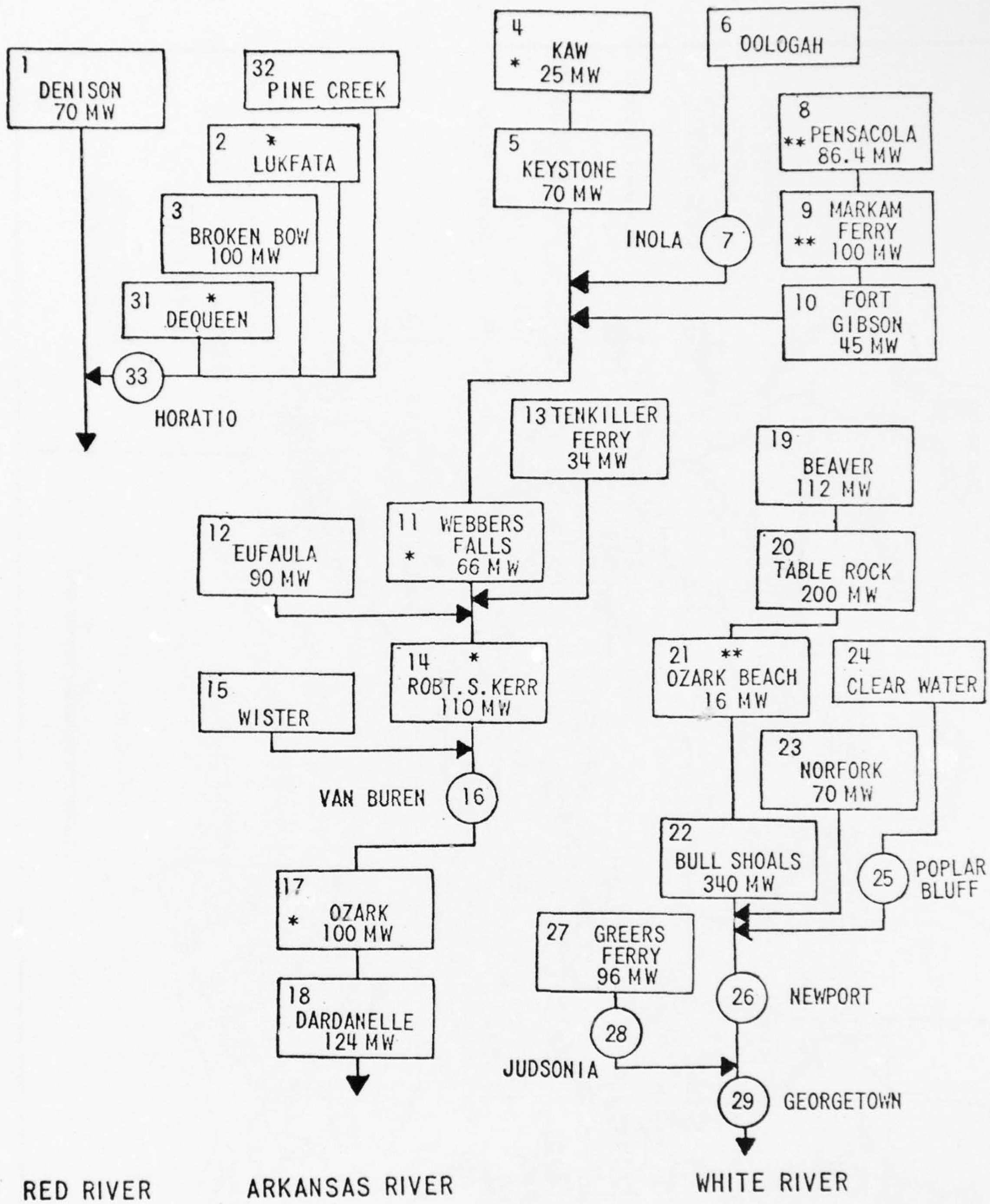
[1]Hydraulic Engineer, Special Assistance Branch, The Hydrologic Engineering Center

At the beginning of the Southwestern Division power system studies in August 1967, programs other than the district programs were considered applicable only for planning purposes. The districts involved wished to develop their own operational programs and use weekly rather than monthly routings. In addition to communication problems within the Corps, which delay use of available programs, it appears that available programs are often evaluated on the basis of the way studies were being done by hand rather than whether an equivalent or satisfactory answer can be obtained with the available programs. It was suggested that it would be very profitable for personnel from division and district offices to consult with other offices when experience in system analysis can be exchanged.



LEGEND
Power Projects
Non-power Projects
Projects not included in study
Control Points
ARKANSAS - WHITE - RED
RIVER BASINS
RESERVOIR SYSTEM
CONSERVATION STUDIES
AUG 69
SCALE OF MILES
0 20 40 60 80 100
MISSISSIPPI
Clearwater
BLACK R.
CURRENT RIVER
ELEVEN POINT R
Newport
Georgetown
WHITE R
NORFORK
STRAWBERRY
WHITE RIVER
GREERS FERRY
Judsonia
LITTLE ROCK
Pine Bluff
ARKANSAS R
Ozark Beach
BULL SHOALS
BUFFALO R
DARDANELLE
NIMROD
TABLE ROCK
BEAVER
OZARK
BLUE MOUNTAIN
Van Buren
FORT SMITH
Pensacola
Markam Ferry
TENKILLER FERRY
FORT GIBSON
BROKEN BOW
GILLHAM
DIERKS
DeQueen
MILLWOOD
Horatio
RED RIVER
ROBT. S. KERR
Wister
Lukfata
Pine Creek
HUGO
Oologah
Inola
TULSA
MUSKOGEE
WEBBERS FALLS
EUFAULA
PAT MAYSE
DENISON
LAKE MURRAY
KEYSTONE
KAW
ELK CITY
COPAN
HULAH
CANEY R
BIRD CR
HEYBURN
DEEP FORK RIVER
CANADIAN RIVER
LITTLE R
NORMAN
MUDDY BOGGY CR
CLEAR BOGGY CR
WALNUT R

PLATE 1



* NOT IN OPERATION

** NON-FEDERAL

◯ CONTROL POINT

ARKANSAS-WHITE-RED RIVERS
SCHEMATIC STREAMFLOW DIAGRAM
HYDRO POWER SYSTEM

DEC 68

PLATE 2

ARKANSAS ITE-RED RIVERS
RESERVOIR SYSTEM CONSERVATION STUDIES

Project	ELEVATION, FT.MSL Top of Cons.Pool	Top of F/C Pool	STORAGE IN 1000 Ac-Ft Cons.	Flood	INSTALLED CAPACITY MW	HEAD** Ft.	DATE PLACED IN OPERATION
WHITE RIVER							
Beaver	1120	1130	925	300	112	191	Apr 63
Table Rock	915	931	1182	760	200	205	Nov 58
*Ozark Beach	701.1	-	13	-	16	48	1930
Bull Shoals	654	695	1003	2365	340	196	Aug 51
Norfork	552	580	707	732	70	175	Jun 43
Clearwater		567	-	391	-	-	Mar 48
Greers Ferry	461	487	716	934	96	185	Mar 62
ARKANSAS RIVER							
Kaw	1013	1044.5	248	866	25	95	Jun 73
Keystone	723	754	351	1216	70	85	Sep 64
Oologah	608	651	49	963	-	-	May 63
*Pensacola	745	755	525	585	86.4	122	Mar 40
*Markham Ferry	619	636	0	244	100	52	Jan 64
Fort Gibson	554	582	54	922	45	60	Jun 52
Webbers Falls	490	-	30	-	66	28	Jun 70
Tenkiller Ferry	634	667	397	548	34	144	Feb 51
Eufaula	585	597	1481	1470	90	99	Feb 64
R.S. Kerr	460	-	80	-	110	44	Jun 70
Wister	471.6	502.5	30	400	-	-	May 49
Ozark	372	-	19	-	100	34	Nov 69
Dardanelle	338	-	65	-	124	49	Oct 64
RED RIVER							
Denison	617.25	640	1706	2638	70	106	Jan 44
Pine Creek	438	480	47	412	-	-	Jun 69
Lukfata	518	586.5	35	207	-	-	In Plan Stage
Broken Bow	599.5	627.5	470	450	100	184	Oct 68
DeQueen	437	473.5	26	101	-	-	Jun 73

*Non-federal
**At top of conservation pool with average tailwater

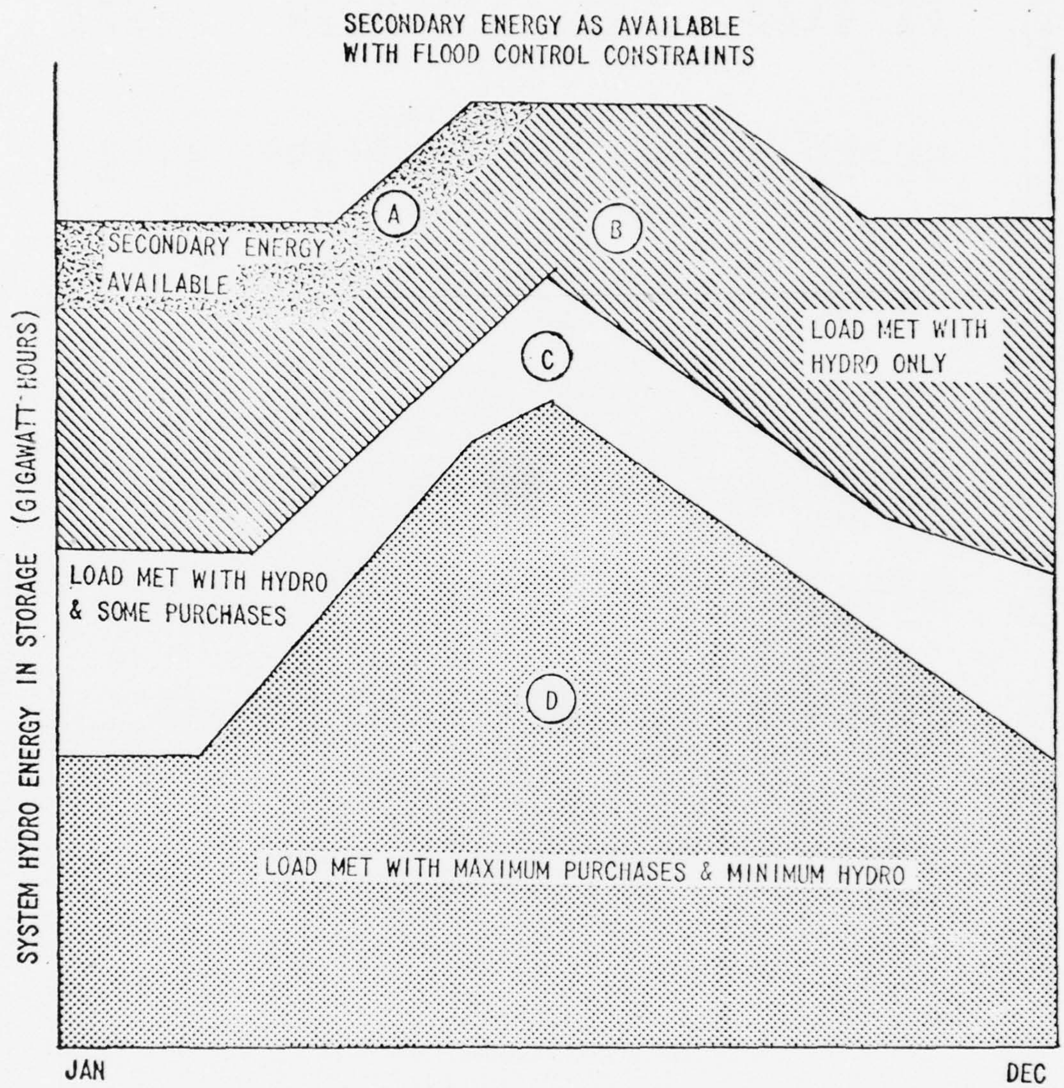


ILLUSTRATION OF SYSTEM
OPERATING CURVES

JUN 1969

PLATE 4

APPLICATION OF SYSTEM ANALYSIS TECHNIQUES TO PROJECT OPERATIONS

By

David M. Rockwood[1]

INTRODUCTION

Techniques for analyzing water resource systems are usually applied in planning and designing water resource developments. These are utilized for a broad variety of studies leading to project justification, scoping, and developing operation criteria. This type of study permits analysis of a complex system of river control works, whereby various alternative solutions can be tested and selections made on the basis of optimal and balanced development, considering all factors including the hydrologic character, engineering considerations, economic evaluations, and social and political values. The analysis by electronic computer has afforded the engineer and planner a powerful tool in river basin planning, in achieving these solutions. The literature is filled with methods and techniques of river basin analysis, ranging from simple linear river and reservoir models, to complex multi-variable water resource system models involving dynamic programming. Nearly all of this work, however, has been oriented to river basin planning, in situations where time of computation and analysis is not the controlling factor in arriving at the solutions.

The work that is to be presented in this paper is oriented to operational system analysis, to be used in the management of waters in a river system on a day-to-day basis. This involves methods that may be applied operationally, in accordance with that much overworked term, "real time". Reference is made to Progress Report of the Task Committee on Hydrometeorological Systems, American Society of Civil Engineers, published in 1967 (reference 1), which outlined among other things the application of river system management models for current operations in water management. While many of the tools to be described in this paper can be used also for planning and design work, the emphasis of the presentation is on the application to operational hydrology and river management practice. For this purpose, the analysis techniques by computer are necessarily systematized to a high degree in order to provide timely simulations of complex hydrologic and reservoir regulation conditions on an assured basis each day, and to provide timely results of alternative solutions for use in management decisions. Furthermore, as more experience is gained in the use of these techniques, arbitrary and inflexible reservoir regulation criteria may be adjusted to meet the ever-changing hydrometeorological conditions as they develop over the drainage basin.

[1] Chief, Hydrology and Hydraulics Section, North Pacific Division.

PURPOSE AND SCOPE

It is the purpose of this paper to present the general features of operational river management methods as presently utilized in the Columbia River Basin. The emphasis is upon the use of the "SSARR" model (Streamflow Synthesis and Reservoir Regulation) in developing streamflow and reservoir regulation forecasts in order to meet the overall water management decisions on a day-to-day basis. The procedures are general in nature, so that the principles may be applied to other river systems. Because of space limitations in this paper, only a general overview of the methods can be presented. Reference is made to other publications which describe the procedures in detail. Finally, a brief summary of results of regulation of the 1967 Columbia River Flood illustrate the application of the model on an operational basis.

THE COLUMBIA RIVER

The Columbia is characterized as the major snow-fed river of the contiguous 48 states. Its quarter-million square mile area drains the rugged mountain regions of the Pacific Northwest largely in the states of Oregon, Washington, Idaho, Western Montana, and also some 39,500 square miles in British Columbia, Canada. Each year, the winter's accumulation of snow in the mountains melts with the warming conditions experienced during the spring and early summer. The runoff from the melting snowpack gradually increases until the annual peak flow is reached, usually during the first half of June.

After the peak, with the ablation of the snowpack, streamflows recede and reach base flow by early fall. Rainfall is usually a minor contributor to streamflow, but occasionally secondary peak discharges occur in the winter from rainfall. Major snowmelt floods are often augmented by rain falling on the melting snowpack. Figure 1 shows the general configuration of the Columbia River system, including the location of major reservoir projects. The streamflow character of the main Columbia is shown in the Summary Hydrograph, figure 2.

Efficient management of Columbia River waters during the hydrologically active period of April through August is extremely important for all of the various project functions, including flood control, hydroelectric power, irrigation, navigation, recreation, and fish and wildlife. About 70 percent of the runoff occurs in this period, and the major reservoirs are refilled for meeting subsequent hydroelectric power or irrigation demands. Because of the ability to forecast seasonal runoff volumes accurately, the amount of reservoir drawdown can be scheduled on a long-range basis, several months in advance of the refill. The timing of the spring runoff, on the other hand, is quite unpredictable on a long-range basis, because it is dependent upon ever-changing meteorological patterns which affect snowmelt. No two years are alike, and the meteorological sequence has a marked effect on the runoff pattern over a two-to-three month period.

FLOOD REGULATION

Particularly with regard to flood control, the timing of the runoff has a marked effect on the efficient use of reservoir storage to control flows to predetermined limits. The amount of usable reservoir storage space of about 20 million acre-feet presently available is about 15 percent of the runoff during a major flood season. With the addition of projects now under construction in both Canada and the United States, the total volume of reservoir storage will be about 25 percent of that runoff volume. The basic objectives of flood regulation are to refill the storage so as to achieve a maximum reduction of the peak discharge in the Lower Columbia River, to assure within-bank flows at potential flood damage areas on tributary streams, to assure refilling the reservoirs, and to meet all project functions during the refill period.

The difference in reservoir storage requirements to control different floods of approximately equal volume is illustrated by the flood season hydrographs shown in figure 3 for the Columbia River at The Dalles, Oregon (DA = 237,000 square miles). The two years, 1954 and 1948, were of approximately equal potential seasonal runoff volume, based on long-range volumetric forecasts made as of April first of each year. In 1948, a critically severe sequence of snowmelt and rainfall conditions occurred during May and June, and a predetermined controlled discharge of 450,000 cfs at The Dalles (presently considered as the maximum non-damaging flow in the Lower Columbia River) would have required 27 million acre-feet of reservoir storage. In 1954, on the other hand, weather conditions were such that the unregulated hydrograph was "flat-topped", as the result of alternate periods of warming and cooling during May and June. In this year, only 6.5 million acre-feet would have controlled the discharge to 450,000 cfs. Other years of equal volume lie within the extremes portrayed by the 1948 and 1954, as shown in figure 4.

In actual flood regulation, the initial controlled flow for the Lower Columbia can be determined on the basis of forecasts of runoff volume and reservoir storage space in order to achieve the maximum flood reduction. Once regulation has begun, the "pulse of the river" must be monitored continuously, in order to maintain continuity of hydrometeorological and snowpack conditions which control the ever-changing potential of runoff. Day-to-day decisions on reservoir regulation are necessarily based on system streamflow and reservoir regulation simulations of future events. These are made for a period of time sufficient to foresee refillability of reservoirs without jeopardizing flood regulation, as well as to meet all other project functions including hydroelectric power, irrigation, navigation, recreation, and fish and wildlife. This objective leads to the requirement for computer synthesis on a near real-time basis, whereby all hydrometeorological and reservoir regulation elements are integrated into an all-purpose digital computer model, for synthesizing streamflows for a period of from 30 to 45 days in advance.

THE "SSARR" MODEL

The computer program developed by the North Pacific Division Office of the Corps for performing the required simulations has been termed the "SSARR" model, as an abbreviation of Streamflow Synthesis And Reservoir Regulation. This model is a general purpose digital computer program which is now in its third generation of development. It was originally designed in 1957 (reference 2) for use on the IBM 650 computer, and from its operational use on a multitude of streamflow simulations for planning, design, and operational hydrologic studies, the scope, techniques and utility of the program for efficient utilization of today's high speed computers have increased many-fold since its original design.

The basic concept of the "SSARR" model is to create a mathematical hydrologic model of a river and reservoir system, whereby streamflows can be synthesized by evaluating the entire hydrologic process of snowmelt and/or rainfall runoff for all significant points throughout the system. Drainage basins can be separated into homogeneous hydrologic units of a size and character which can be used as a logical delineation of a major basin into its component sub-drainages. Channel storage can be specified for channel reaches to represent the natural delay to runoff encountered in river systems. Storage effects of natural lakes or manmade reservoirs can be evaluated in accordance with free-flow conditions or specified conditions of reservoir storages or withdrawals. Thus, the program contains the ability to access three basic elements, as follows:

1. A generalized hydrologic watershed model for synthesizing runoff from snowmelt, rainfall, or combination thereof, as drainage basin outflows.

2. A river system model, for routing streamflows from upstream to downstream points, including the ability to route flows as a function of multi-variable relationships involving backwater effects from tides or reservoirs, in a generalized manner for representing any desired river configuration.

3. A reservoir regulation model, whereby predetermined or synthesized reservoir inflows may be operated upon in accordance with several modes of reservoir regulation as a time series, or as free flow, within given constraints and specified reservoir characteristics.

Principal considerations in the design of the model components were to: (1) utilize practical and theoretically sound techniques in evaluating hydrologic processes; (2) utilize storage routing techniques as developed specifically for this model, whereby the computational process may be initialized at any time in the simulation processes and thereby preserve the continuity of all time dependent functions as developed from prior

computation on a day-to-day basis; (3) develop necessary hydrologic and/or channel characteristics either from empirical trial-and-error techniques, or from known physical data; (4) provide for flexible methods of specifying functional relationships used in the simulation; (5) simplify the input data formats as much as possible, in order to operate the model with a minimum of data preparation on a day-to-day basis; (6) utilize bulk random access data storage devices (disc storage units) for storing characteristic and time dependent data files, program elements and working files; (7) develop the model in a completely generalized way, whereby it may be applied to any basin, streamflow or reservoir system, of any desired configuration or hydrologic requirement; and (8) provide for the model to adjust itself to specified or observed conditions of streamflow from previously computed amounts, and maintain continuity of functions in further processing. It is not within the scope of this paper to describe the details of the techniques utilized. Reference is made to recent technical papers which present the basic elements of the program (references 3-6). The program is written in FORTRAN IV, and is presently operating on the IBM 360/50 Computer System installed in the North Pacific Division Office of the Corps of Engineers.

INPUT DATA

Various types of input data are necessary for operation of the model, in the following categories:

I. Non-variable characteristic data.

A. Watershed basin runoff functional data and relationships, expressed individually for each basin.

B. Channel characteristic fun ctional relationships, expressed individually for each channel reach.

C. Reservoir characteristic functional relationships, expressed individually for each lake or reservoir.

D. Tables of functions used in any of the above-listed relationships.

E. Local inflow, river control points or river diversion definitions.

F. Configuration definition for specifying the relative downstream ordering of tributary basins, channel reaches, reservoirs, or diversion points.

II. Initial-conditions data, for specifying time, t_o, conditions of all basin snowmelt runoff indexes, forecasts of total runoff volume, streamflow routing conditions, and reservoir conditions, individually for all contributing areas, channel reaches, and reservoirs for which the simulation is to be performed.

III. Time variable data.

A. Hydrometeorological elements, expressed as time series for the forecast period.

1. Precipitation data for individual basins

2. Snowmelt function data for index stations

a. Air temperature index values

b. Thermal budget values

3. Local inflows for certain non-responsive contributing areas.

B. Reservoir regulation data, expressed as a time series for each project.

IV. Miscellaneous job control and time control data.

THE COOPERATIVE COLUMBIA RIVER FORECASTING UNIT

In order to coordinate river forecasting activities and to make full use of the SSARR model for streamflow forecasting and reservoir regulation in the Columbia River Basin on an operational basis, the Cooperative Columbia River Forecasting Unit was formed in 1963, under agreement made at the Washington level of the agencies involved. This unit, presently comprised of river forecasting elements of the US Army Corps of Engineers, North Pacific Division and the Portland River Forecast Center, US Weather Bureau, ESSA, provides the means of centralizing forecasting and river regulation activities to meet the requirements of both agencies. The overall objectives of the unit are: (1) to make best use of available computer facilities and trained river forecasting specialists of the agencies involved; (2) to advance techniques in all phases of river forecasting as related to river management; (3) to provide coordinated operational forecasts on a long-, medium- and short-range basis for the common use of both agencies in meeting their respective missions; and (4) to centralize the river intelligence in a river operation center for daily briefings. By meeting these objectives, the operation of the unit jointly by the two agencies has resulted in great efficiencies by coordinating forecasts as required for specific agency use, and by preventing duplication of effort.

APPLICATION OF THE SSARR MODEL FOR COLUMBIA RIVER FORECASTING

The application of the SSARR model to the Columbia Basin involves daily simulations of streamflows each year beginning in April, at the time of the initial major rises of streamflow, and continue until it is assured that all danger of flooding is past and reservoirs are refilled. The

forecast period is generally 30 days, but occasionally, the simulations are performed for 45 days in advance. Inasmuch as weather forecasts are reliable only for about 3 to 5 days in advance, the hydrometeorological factors affecting runoff must be extended during the runoff forecast period on the basis of either normal or maximum snowmelt conditions, and both condiditons are run each day to assess runoff potentials. Inasmuch as regulation for flood control is concerned primarily with the potential for maximum streamflows that might develop with adverse weather conditions, the refill of downstream reservoirs is based largely on reservation of sufficient storage space to assure control of the flood under these conditions. Then, as the potential gradually decreases, the day-to-day regulation is accomplished to assure the orderly refill of storage and meet all at-site and downstream requirements for the system as a whole. The streamflow simulations provide the necessary information for making logical operating decisions.

The simulations for the Columbia River presently involve the following numbers of sub-basin watersheds or local inflow catchments, channel reaches, reservoirs, and downstream control points:

a.	Sub-basin watershed runoff catchments	67
b.	Channel reaches	47
c.	Reservoirs	28
d.	Downstream control points	68

The logical delineation of the Columbia is based largely on the locations of streamgaging stations which are included in the daily reporting network, and on project locations. Data on streamflow, air temperature, precipitation, reservoir conditions, and conditions of the snowpack are reported daily, through the interagency cooperative hydrometeorologic reporting network. The reports are generally received daily between 7:30 a.m. and 9:00 a.m., local time through the Columbia Basin Teletype System. The reports on main stem reservoir projects are transmitted hourly by teletype. All reports are analyzed for consistency, interpreted, and converted to the form necessary as input to the SSARR model. Forecasts of weather conditions are made, including quantitative precipitation for each sub-basin and temperature index values, at some 20 index stations and put in computer form. Key punching of all required input data is accomplished by 10:00 a.m., machine runs are made by 11:00 a.m., and the forecasts become the basis for operating decisions which are relayed to the projects by teletype as operating instructions for the ensuing 24-hour period.

EXAMPLE OF FLOOD REGULATION

The 1967 Columbia River Flood serves as an example of optimum reservoir regulation, which was accomplished largely with the aid of the SSARR model, through the coordinated forecasting effort of the Cooperative Columbia River Forecasting Unit. In that year, only about 10 million acre-feet of usable storage were available for downstream river control. Forecasts of seasonal runoff volume, made as of 1 April, indicated about 108 percent of normal runoff for the basin as a whole. Furthermore, during the pre-flood period of April and early May, weather conditions

were such that the potential for serious flooding increased. Precipitation was generally above normal, and temperatures were below normal, so that a relatively larger proportion of the snowpack remained in the mountain areas in mid-May. There was general concern in the lower Columbia River areas of a possible repetition of the 1948 flood sequence. Upstream reservoirs, which are regulated on the basis of fixed regulation criteria, were operated to store their share of the flood waters, on the basis of seasonal volume forecasts. The Bureau of Reclamation's Grand Coulee project at that time provided the major downstream reservoir control, and this storage is operated on a day-to-day basis in response to the flow increases during the major spring rise accompanying the peak of the flood. About 2,000,000 acre-feet of storage space were available at Grand Coulee in mid-May 1967, and it was held for final regulation of the flood peak in June.

On 8 June, the flow of the Columbia approached 600,000 cfs. From the simulations, it was possible to determine at that time, that the peak could be held to this value of discharge through the remainder of the flood, even with adverse snowmelt conditions for the remainder of June. Accordingly, it was decided to regulate the flow to approximately 600,000 cfs. As it turned out, above-normal snowmelt, augmented by rainfall, did occur in mid-June, but there was sufficient space in the reservoirs to control the flow to this level. All project purposes were met, and the reservoirs were essentially filled by the end of June.

Figure 5 shows the results of the 1967 flood regulation for the Columbia River at the Vancouver, Washington gage. At this point, flood damage begins at a river stage of 16 feet, and the major flood level is 26 feet. The regulation reduced the flood about 5.0 feet, from 26.5 feet to 21.5 feet, and the river was held at its maximum level of about 21.5 feet for a period of about 25 days. Considering the relatively small amount of storage space available, this was near-optimum regulation. The benefits from flood reductions in the Lower Columbia for 1967 amounted to 14,200,000 dollars.

RECENT USAGE OF THE SSARR MODEL

As indicated previously, the SSARR model has been applied to a variety of hydrologic and reservoir regulation problems in NPD, other than for operational use for day-to-day river management. It is not in the scope of this paper to describe these uses, but these are discussed in Disposition Form, Subject, "Summary of Recent Applications of SSARR Model", dated 25 February 1969, which summarizes the analyses in NPD performed on this model from the period July 1967 to February 1969. Specific reference is made to table 1 of that memorandum, which is reproduced here for convenience. These listings include only those applications made on the so-called "Third Generation" of the SSARR model.

TABLE 1

SSARR (STREAMFLOW SYNTHESIS AND RESERVOIR REGULATION) COMPUTER PROGRAM

SUMMARY OF COMPLETED APPLICATIONS SUBSEQUENT TO REDESIGN FOR IBM 360 COMPUTER SYSTEMS

JULY, 1967 - FEBRUARY, 1969

STUDY ITEM	SCOPE OF APPLICATION			TYPE OF USAGE	
	Major Comprehensive Multi-Basin	Minor Multi-Basin	Single Basin	Continuous	One Time
I. Design Flood Studies (NPD)					
A. Chief Joseph Probable Maximum Flood	X				X
B. Dworshak Probable Maximum Flood			X		X
C. Blackfoot Probable Maximum Flood		X			X
D. Payette Standard Project Flood		X			X
E. Bonneville Probable Maximum Flood	X				X
F. Lower Columbia Standard Project Flood	X				X
G. Chena River Probable Maximum & Standard Project Floods		X			X
II. Reservoir Regulation Studies					
A. Columbia River Flood Regulation	X			X	
B. Grande Ronde		X			X
III. Operational Forecasting and Reservoir Regulation					
A. Columbia River	X			X	
B. Willamette River	X			X	
C. Western Washington					
1. Cowlitz River			X	X	
2. Nooksak			X	X	
3. Snohomish			X	X	
4. Green River			X	X	
IV. Special Studies Related to Forecasting					
A. South Yamhill River			X		X
B. McKenzie River			X		X
C. Columbia Basin	X			X	
1. Snowmelt Flood	X			X	
2. Reconstitution Studies	X			X	
D. Willamette Basin Trib. Reconstitution Studies	X			X	
V. Mekong River Studies					
A. General Hydrology Studies	X				X
B. Reservoir Regulation Studies	X				X
C. Design Flood Studies					
1. Luang Prabang	X				X
2. Pakse	X				X
3. Sambor	X				X
VI. International Hydrologic Decade					
A. Mekong Study	X			X	
B. Willamette Basin Lab Study	X				X

FUTURE DEVELOPMENTS OF RIVER SIMULATION TECHNIQUES

The development of river analysis techniques, such as are included in the SSARR model, is a never-ending process. Continuous usage of the SSARR model in the North Pacific Division not only for operational forecasting and river regulation, but also for application to numerous other hydrologic engineering studies over the past 12 years, have led to major improvements in hydrologic and reservoir regulation design, and computer utilization. Each of the three successive efforts in program development have built upon the experience gained in actual operation, particularly with regard to day-to-day river regulation. Even now, we look forward to additional program capabilities with respect to several major areas, as follows:

1. Ability to regulate reservoirs on the basis of downstream specifications in a multi-reservoir system.

2. Ability to compute hydroelectric power capability (both daily energy and peaking capacity) and regulate streamflows in the interest of power requirements.

3. Ability to synthesize streamflow in the watershed model by elevation bands, for operational forecasting.

4. Establishment of master run files, and numerous data processing refinements.

In addition, numerous minor modifications in hydrologic and reservoir regulation techniques are constantly being added within the framework of the basic set of programs included in the SSARR model. Accordingly, the model is not static, but is continually being upgraded.

SUMMARY AND CONCLUSIONS

In summary, the application of system analysis to operational hydrologic and day-to-day river management has been accomplished for the Columbia River Basin, in a process of development over the past 12 years. The basic SSARR model has been developed for this purpose, and it is being used routinely by the Cooperative Columbia River Forecasting Unit (presently comprised of forecasting elements of the North Pacific Division Office of the Corps of Engineers and Portland River Forecast Center, US Weather Bureau) in meeting their respective responsibilities in day-to-day reservoir regulation and streamflow forecasting. The SSARR model is general in nature, and has been applied to river systems fed by snow, rain, or combined rain and snow. The model is in a continual process of development as experience is gained in its use. Details of its design and application are contained in technical publications referenced herein.

REFERENCES

1. "Hydrometeorological Systems", Progress Report of the Task Committee on Hydrometeorological Systems of the Committee on Hydrometeorology, Journal of the Hydraulics Division, ASCE, vol. 93, no. HY4, Proc. Paper 5342, July, 1967, pp. 99-115.

2. Rockwood, D.M., "Columbia Basin Streamflow Routing by Computer", Journal of Waterways and Harbors Division, American Society of Civil Engineers, Dec. 1958, vol. 84, part 1, Paper no. 1874.

3. Davis, E.M., "Draft of Operating Instructions Computer Program for Streamflow Synthesis and Reservoir Regulation", US Army, June 1967.

4. Rockwood, D.M., "Application of Streamflow Synthesis and Reservoir Regulation - "SSARR" - Program to the Lower Mekong River" presented at Symposium on Use of Analog and Digital Computers in Hydrology, Tucson, Arizona, 8-15 December 1968.

5. Kuehl, D.W. and Schermerhorn, V.P., "Hydrologic Digital Model of Willamette Basin Tributaries for Operational Forecasting, " U.S. Weather Bureau River Forecast Center, Portland, October 1967.

6. Schermerhorn, V.P. and Kuehl, D.W., "Operational Streamflow Forecasting with the SSARR Model", U.S. Weather Bureau River Forecast Center, Portland, December 1968.

SUMMARY OF DISCUSSION

Compiled by R. G. Willey[1]

Mr. Beard pointed out that the Waterways Experiment Station (WES) is contemplating the development of a mathematical computer model for the Mississippi River Basin and that some features of the SSARR program might be useful to them. Mr. Rockwood considers that the program description and the technical reports on SSARR are probably sufficiently clear to enable WES to assess the techniques and to extract what they can use. Of particular value are the data handling techniques, which took great efforts to develop. Large complex comprehensive program models must be generalized and packaged so that routines can easily be extracted for use in other generalized models. Generalized programs must allow for alternative methods of solution where appropriate; e.g., allow user selection from various channel routing methods. SSARR has concentrated on generalization of input; allowing the user selection of various input methods and quantities of input data.

Future plans for SSARR development include optimization techniques for the automatic selection of reservoir releases on the basis of downstream conditions, rather than the present method of specifying releases as a function of reservoir storage. This present method does not seriously impair the use of the SSARR model in the Columbia Basin, because of conditions prevailing in that basin. The SSARR model has also been used on the Willamette Basin, where runoff is primarily from rainfall. Application to other areas or regions requires proper knowledge and indoctrination, but the basic framework of the model and the generalized nature of the program design allows great flexibility in adapting it to regions of varying hydrologic and system conditions.

The paper refers to the model's ability to handle 68 downstream control points. The term "control points" is used to mean locations where inflow data can be synthesized and does not necessarily mean a local point for stage or flow control.

The Cooperative Columbia River Forecasting Unit is a joint effort by the Corps and the Weather Bureau to satisfy the needs of both agencies. It has worked extremely well and efficiently because of good interagency relations. The Hydrologist-In-Charge is a Weather Bureau employee. The SSARR model is used with Corps reservoir release data and Weather Bureau precipitation data to develop a joint forecast.

[1]Hydraulic Engineer, Training and Methods Branch, The Hydrologic Engineering Center


EXIST. MAJOR PROJECTS
MAJOR RESERVOIR PROJECTS
UNDER CONSTRUCTION
COLUMBIA
RIVER
BASIN
MICA
DUNCAN
KOOTENAY
LAKE
ARROW
Trail
CANADA
U.S.
Bonners
Ferry
LIBBY
HUNGRY
HORSE
GRAND
COULEE
CHIEF JOSEPH
WELLS
NOXON
ALBENI
FALLS
FLATHEAD
LAKE
ROCKY
REACH
ROCK
ISLAND
SEATTLE
WANAPUM
LOWER
MONUMENTAL
LITTLE
GOOSE
WASH.
PRIEST
RAPIDS
DWORSHAK
ICE
HARBOR
LOWER GRANITE
THE
DALLES
JOHN
DAY
IDAHO
McNARY
BONNEVILLE
PORTLAND
CASCADE
BROWNLEE
DEADWOOD
JACKSON
LAKE
BOISE PROJECTS
PALISADES
OREGON
FIG. 1

SUMMARY HYDROGRAPH

COLUMBIA RIVER NEAR THE DALLES, OREGON

DRAINAGE AREA = 237,000 SQ. MI.

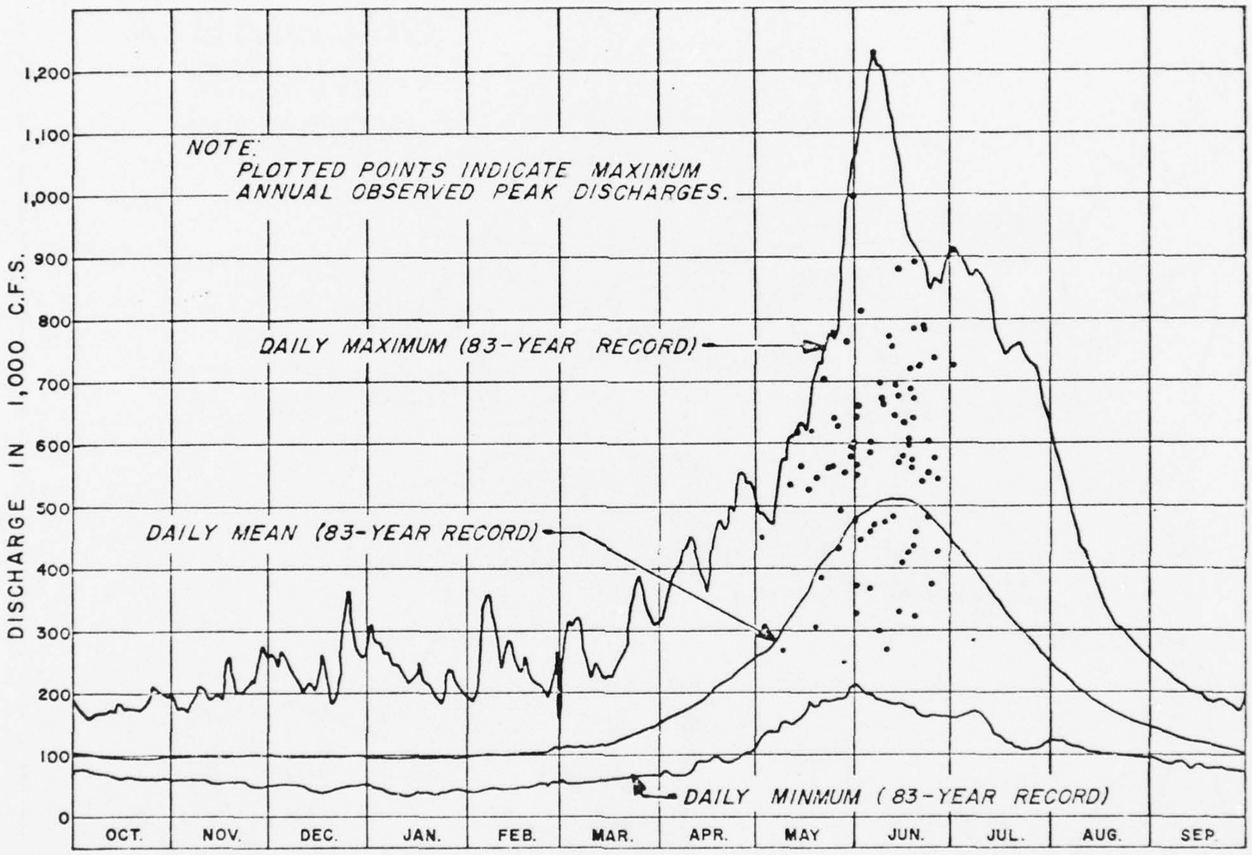
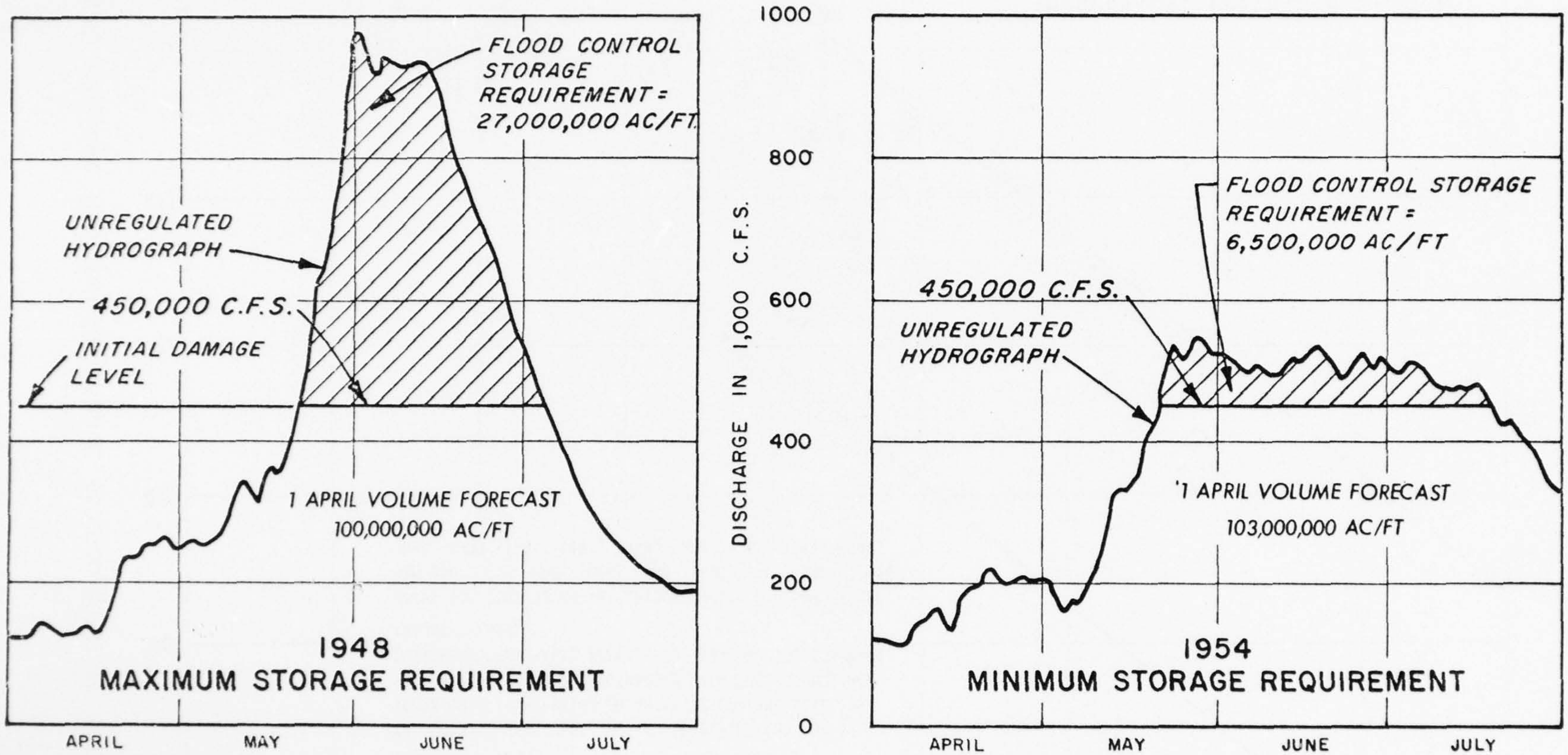


FIG. 2



COMPARATIVE FLOOD REGULATION REQUIREMENTS
1948 AND 1954 FLOOD SEASONS

FIG. 3

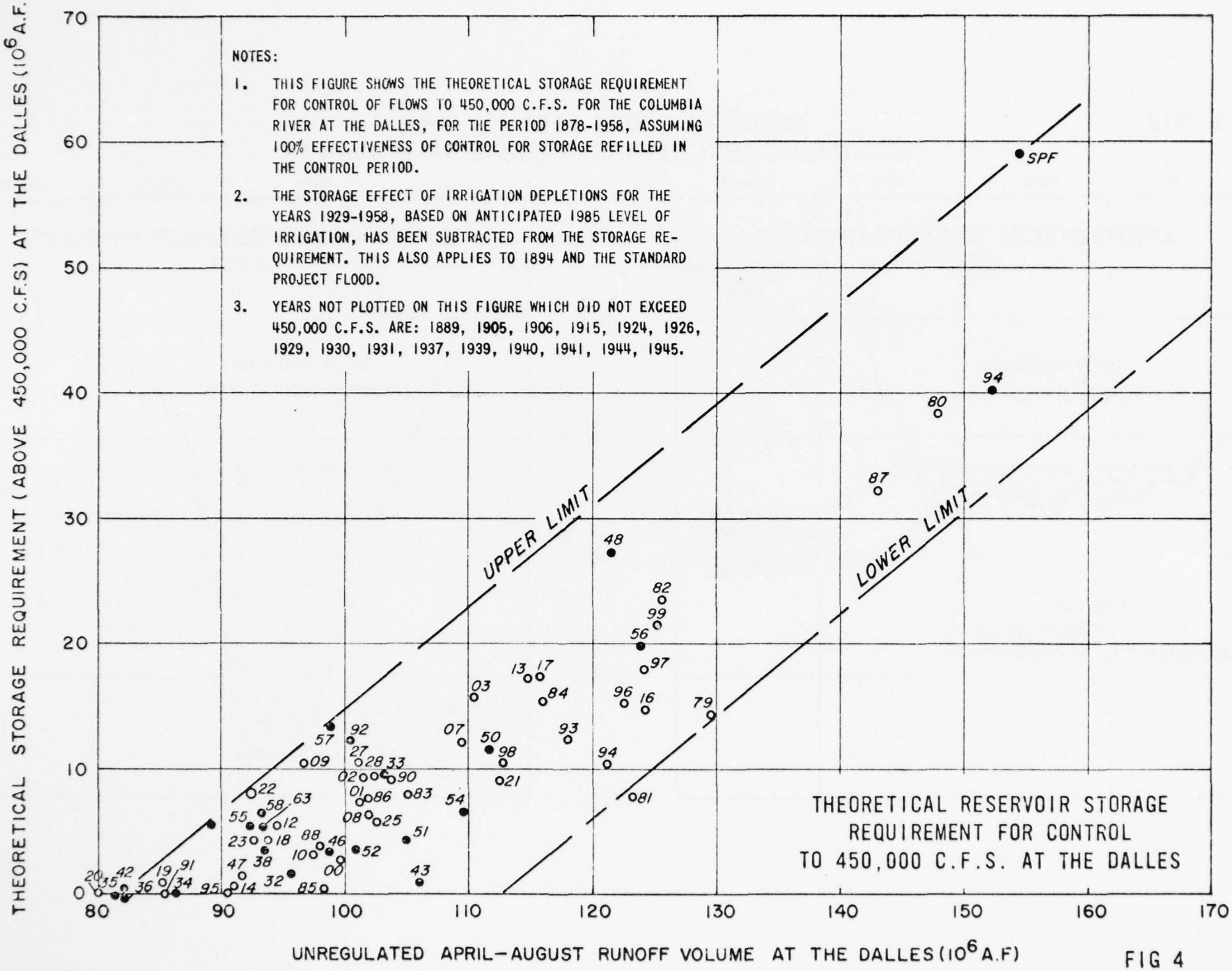

NOTES:
1. THIS FIGURE SHOWS THE THEORETICAL STORAGE REQUIREMENT FOR CONTROL OF FLOWS TO 450,000 C.F.S. FOR THE COLUMBIA RIVER AT THE DALLES, FOR THE PERIOD 1878-1958, ASSUMING 100% EFFECTIVENESS OF CONTROL FOR STORAGE REFILLED IN THE CONTROL PERIOD.
2. THE STORAGE EFFECT OF IRRIGATION DEPLETIONS FOR THE YEARS 1929-1958, BASED ON ANTICIPATED 1985 LEVEL OF IRRIGATION, HAS BEEN SUBTRACTED FROM THE STORAGE REQUIREMENT. THIS ALSO APPLIES TO 1894 AND THE STANDARD PROJECT FLOOD.
3. YEARS NOT PLOTTED ON THIS FIGURE WHICH DID NOT EXCEED 450,000 C.F.S. ARE: 1889, 1905, 1906, 1915, 1924, 1926, 1929, 1930, 1931, 1937, 1939, 1940, 1941, 1944, 1945.
UPPER LIMIT
LOWER LIMIT
SPF
THEORETICAL STORAGE REQUIREMENT (ABOVE 450,000 C.F.S) AT THE DALLES (10^6 A.F.)
UNREGULATED APRIL-AUGUST RUNOFF VOLUME AT THE DALLES (10^6 A.F)
THEORETICAL RESERVOIR STORAGE
REQUIREMENT FOR CONTROL
TO 450,000 C.F.S. AT THE DALLES

FIG 4

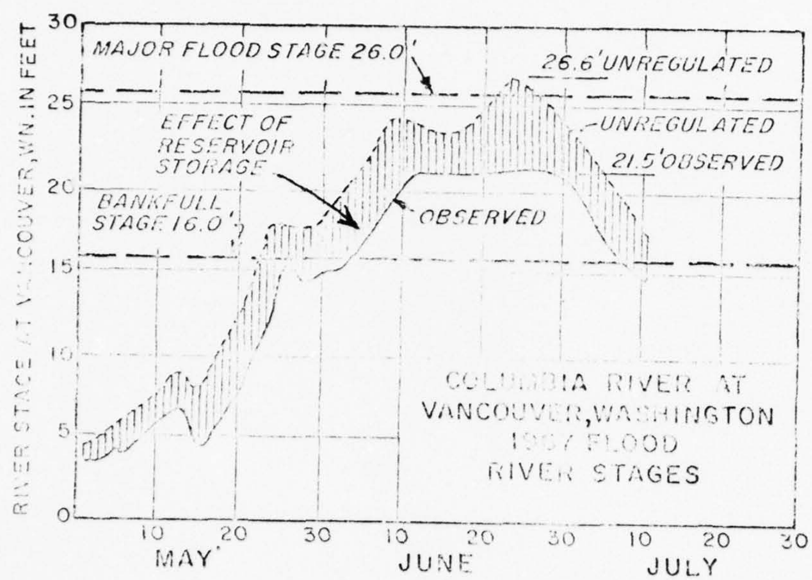

RIVER STAGE AT VANCOUVER,WN. IN FEET
30
25
20
15
10
5
0
MAJOR FLOOD STAGE 26.0'
26.6' UNREGULATED
EFFECT OF RESERVOIR STORAGE
UNREGULATED
21.5' OBSERVED
BANKFULL STAGE 16.0'
OBSERVED
COLUMBIA RIVER AT
VANCOUVER,WASHINGTON
FLOOD
RIVER STAGES
10 20 30 10 20 30 10 20 30
MAY
JUNE
JULY

FIG.5

INTEGRATED SYSTEM ANALYSIS FOR MULTIANNUAL REGULATION STUDIES
MISSOURI RIVER MAIN STEM RESERVOIR SYSTEM

by

Maurice A. Clare[1]

The Missouri River Main Stem Reservoirs, constructed by the Corps of Engineers, extend through eastern Montana, a large part of North Dakota and practically the entire state of South Dakota, terminating just upstream from Yankton, South Dakota on the Nebraska-South Dakota border. At full pool, the reservoirs inundate over 750 miles of the Missouri valley and store about 75 million acre-feet, the equivalent of 3.5 times the average annual runoff originating above the system under current basin development conditions. About 90 percent of this storage space is located in the three upstream projects, Fort Peck, Garrison and Oahe, seven percent is in Fort Randall and the remaining three percent in Big Bend and Gavins Point. As could be expected, the latter two are essentially run-of-the-river projects. Locations of projects are shown on plate 1.

Total storage space in each of the projects (with the exception of Fort Peck) was essentially determined by site limitations. The total space has been divided, as indicated by current storage allocations, into four types of storage consisting of:

1. Inactive, 23 percent of the total space, designed to maintain minimum power heads and recreation pools and which served as a basis for design of pumping installations from the reservoirs.

2. Carryover multiple-use, 55 percent of the total space, designed to provide for the water demand functions of the system through a drought period of several years duration.

3. Annual flood control and multiple-use, 16 percent of the total space, designed for the control of the majority of flood occurrences and the subsequent utilization of this stored water for multiple-use functions on an annual basis.

4. Exclusive flood control, six percent of the total space, provided, as its name implies, only for the control of floods.

The contributing drainage area above the system of 280,000 square miles is about one-half of the total Missouri Basin drainage area and is characterized by extremes of climate and runoff. Annual runoff above Gavins Point has ranged from less than 11 million acre-feet to over 35 million acre-feet and normally has distinct seasonal characteristics. The melt of

[1] Chief, Reservoir Regulation Section, Missouri River Division

the plains snow cover in March and early April, augmented by ice jams on tributary streams, usually produces the maximum crest inflows of the year. Snowmelt from the mountainous drainage area during May through July, augmented by rainfall runoff over the entire drainage area, usually produces greater volumes but lower crests than the earlier plains snowmelt period. During the remainder of the year, runoff is usually low, although occasionally rainfall will produce substantial runoff. The winter season is characterized by ice-covered streams and low runoff amounts. Over 70 percent of the annual runoff normally occurs in the 5-month period, March through July.

In addition to the main stem reservoir system, water resource development, which has an effect of depleting or redistributing the natural water supply of the basin, has been progressing in the Missouri Basin for the past 100 years. Much of this development is associated with irrigation, and it is estimated that at the present basin development level, about 12.5 million acre-feet is depleted annually from the "virgin" water supply. These depletions are expected to continue to increase to a level approaching 30 million acre-feet annually by the year 2020. Many tributary reservoirs, both above and downstream from the main stem reservoir system, have been and will continue to be developed to serve irrigation as well as flood control and other functions normally associated with reservoir development.

Functions that the main stem system was designed to serve include:

1. Flood Control. This function requires the system storage to be drawn down to a pre-determined level prior to the flood season. During this season, the annual flood control and multiple-use space is deliberately filled to the extent that the available water supply exceeds release demands. The annual flood control storage space is adequate to control most floods; however, the system's exclusive flood control space is utilized as necessary to control extreme floods.

2. Irrigation. Most of the surface-water irrigation in the basin is served by tributary streams. The effect of this irrigation on main stem reservoir operations is recognized by consideration of the depletion of inflows into and below the system. Irrigation of about 1.5 million acres in the eastern Dakotas by diversions from Garrison and Oahe is planned. Private irrigation pumping from the Missouri River below several of the reservoirs is increasing and requires maintenance of certain minimum releases.

3. Navigation. The Missouri River navigation project presently extends from Sioux City, Iowa, to the mouth of the Missouri River. No locks are involved, and depths are obtained by the maintenance of adequate flows through this reach of the river, supplemented by dredging. Releases from the main stem reservoirs are scheduled to supplement inflows originating below the system in order to maintain the flows necessary for navigation.

Progressively higher Missouri River flows are required from upstream to downstream portions of the navigation project. To reduce dredging requirements while allowing greater loading depths of tows, as high a flow level as practical is advantageous to this function. Due to ice formation, navigation is generally limited to an 8-month season, April through November.

4. Hydroelectric power. Each of the main stem projects has a hydropower installation with a maximum release capability generally well below the open water channel capacity immediately below the respective plants. However, during the winter ice cover season, release restrictions due to ice are necessary, particularly below the downstream Gavins Point project. Due to the extremely cold winters over the marketing area, peak firm energy demand occurs during this season. Power is marketed by the Bureau of Reclamation.

5. Water supply and water quality control. Minimum releases from each of the projects are established to meet these requirements.

6. Recreation. This function is served by the existence of the reservoirs with their minimum pools. However, it is enhanced by the maintenance of near-full pools with a minimum variation in water surface elevations. Releases from the reservoirs also serve this function on the open river below the projects.

7. Fish and wildlife. This function is also served to a degree by the existence of the reservoirs and their surrounding habitat. It is enhanced by appropriate pool level manipulations designed to encourage the growth and subsequent inundation of spawning habitat and by the maintenance of reservoir releases compatible with the function.

While some of the various functions described above may be compatible in that the provision for one will also serve the needs of the other, they often will be incompatible, particularly in the degree and timing of service. An obvious illustration of incompatibility is the need for maintenance of evacuated storage space for the control of subsequent floods as compared to the need to maintain the maximum amount of storage to provide for increased power heads and the sustenance of water use functions such as navigation and power generation during a possible subsequent drought period. Conflicts in water use arise particularly during periods of subnormal inflow, such as conflicts between the release of water from the system during the winter period, which is of great benefit to power but of no benefit to navigation, and high releases during the open water navigation season, which are of benefit to navigation but result in energy generation at low dump-power rates. Numerous other conflicts in water or storage space use could be cited where the provision of service to one function is detrimental to another of the system functions.

The degree of service to be provided to individual functions is further complicated by the large amount of carryover storage space provided

in the system. During a minor short-term drought period (1 to 2 years in duration) this large amount of available storage enables the maintenance of essentially full service to the water demand functions of the system. However, during long term droughts, comparable to that experienced in the 1930's when inflows to the system in 12 successive years were substantially below normal, a sharp reduction in the level of service provided to these functions is required. The earlier in the drought period that these reductions can be initiated, the less severe will their impact be throughout the period. Another complicating factor is the growth in depletions to streamflow which eventually is expected to result in the loss of over one-half of the "virgin" streamflow above the main stem system.

Over the years, beginning at the time that the reservoir system was in its initial planning stages and extending to the present time when the system is in full operation, numerous long-term regulation studies of the system have been made. These have served various purposes including the demonstration of adequacy of storage allocations to serve their intended purpose, the formation of a basis for cost allocations, the establishment of general regulating criteria which will result in a comparable degree of service tc the various primary functions of the system, and the analysis of effects of increasing basin development upon functions and regulation criteria. To date, all studies have been confined to the period for which actual flow records are available, extending from 1898 to the present time. Originally the studies were made manually, and each study represented a major undertaking, an undertaking of such magnitude that the utilization of completely objective regulating criteria and the detailed examination of the effects of varying these criteria was impractical. In addition, it was necessary to terminate the basin "model" almost immediately below the main stem system, thereby neglecting detailed considerations which are necessary in defining navigation releases.

As electronic computers became available, it became practical to examine regulating criteria in much more detail and to expand the model to encompass the entire main stem of the Missouri River from Fort Peck to the mouth. The first effort to utilize computers for analysis of main stem reservoir operations occurred in 1953, when a contract was negotiated with the Raytheon Company for this purpose. While the results of this contract were disappointing, it did serve as an impetus for computer utilization and pointed out the need for personnel thoroughly familiar with all aspects of system regulation to be involved in all of the details of computer program development. Subsequent efforts toward computer utilization have been conducted by personnel of the Missouri River Division. The program currently in use has over 100 constants and about 75 tables which describe the physical characteristics of the system and define regulating criteria for each of the reservoirs comprising the system. These constants and tables may be modified to reflect changes in characteristic or criteria which may be assumed to occur or the effects of which may need to be examined for an extended period of time. While a study examining a period of record approaching 70 years in duration involved several man-months of effort by manual procedures, it is now

possible to expand the detail and make a completely objective study at the rate of about 30 seconds per year on the medium-speed computer (RCA 301) available to the MRD. The program is coded in both machine language and Fortran II; however, the Fortran code is very inefficient on the available computer.

The model assumed in the program divides the Missouri River into 11 reaches, with reach boundaries defined by main stem reservoirs and navigation control points below the reservoir system. Regulation is performed sequentially, period by period, in intervals ranging from one-quarter month to one month in duration. Input consists of the following:

1. Reach inflows in acre-feet per month. These may be historical or as adjusted to any assumed level of basin development. Prior to about 1930, historical records were largely limited to stage records along the main stem of the Missouri River and scattered or intermittent stage and discharge records for tributary streams. Due to this lack of flow data prior to 1930, the basin development (particularly irrigation) which has taken place through the years, and to obvious inconsistencies in available streamflow records, the development of consistent reach inflows for the period of record extending as far back as 1898, is a major undertaking. Although developed inflows are now in use, their refinement is a subject of continuing study.

2. Depletions or adjustments to reach inflows on a month-by-month basis through the record period. The development of these adjustments to historical reach inflows, or adjustments which will reflect future basin development within the reach boundaries, also presents a major undertaking. The monthly adjustments must be consistent with the available water supply and must consider many diverse factors including the regulation afforded by tributary reservoirs, agricultural practices, irrigation withdrawals and return flows, ground-water development, and other factors which deplete or redistribute the available water supply. The development of these adjustments, consistent with the water supply, essentially requires operation studies which consider all of these factors for each of the reaches throughout the examined record period.

3. Main stem reservoir evaporation. Net evaporation from the nearly 2,000 square miles of main stem reservoir surface (at full pools) is a significant volume, approaching 2 million acre-feet in some years. By an examination of factors which influence evaporation rates and actual precipitation which has occurred, the annual evaporation depth in feet was developed for each reservoir for each year of the record period. Monthly distribution is based on experienced pan evaporation and reservoir water surface temperatures.

4. Flood control release limitations. Since the regulation studies are performed essentially on a month-by-month basis, it is not possible to incorporate detailed release scheduling for flood control purposes which must be adjusted on a daily or shorter time interval. However, by a detailed examination of the records, it was possible to develop a limiting volume of release for each month of the entire record period which recognizes this important function.

5. Water quality control requirements. Minimum system releases to serve this purpose are specified for each month of the entire period of record.

General principles which are incorporated in the criteria to serve specific functions are as described below:

1. Flood control. In addition to the limitation on system releases described above, regulation is designed to evacuate all of the flood control storage space which has been stored during the current flood season for either flood control or multiple-use purposes prior to the succeeding flood season. The timing and extent of this evacuation from period to period and from each of the specific reservoirs is subject to variation by specific criteria incorporated in the program. Maximum allowable releases from each project dictated by the flood control function are incorporated as constants.

2. Irrigation. Service to this function has priority over other water use functions. Therefore, service to these other functions is reduced when necessary to maintain storage reserves in the reservoirs to supply irrigation needs. Irrigation withdrawals directly from the main stem reservoirs are treated as depletions to the appropriate reach, similar to the adjustments resulting from tributary irrigation which were discussed earlier. Minimum releases from each project required to satisfy irrigation withdrawals from the Missouri River below each of the projects are specified as constants.

3. Navigation. Service provided to this function is assumed to vary directly with the amount of stored water available in the main stem system. The service is measured by two means, the level of flows provided to downstream navigation control points and the length provided to each navigation season within the limits resulting from ice formation on the Missouri River. Regulation for this function must consider the usable inflows originating between the system and the downstream navigation control points. There is considerable latitude available for varying specific regulation criteria to serve navigation.

4. Hydroelectric power. A seasonal power load curve is included with the criteria for the purpose of defining the minimum generation which is acceptable during any month of the study. The load requirements defined by this curve vary directly with the amount of storage in the reservoir system. In addition to meeting the requirements defined by the load curve, effort is made to pattern the generation in excess of the minimum

according to the load curve and to reduce releases bypassing any particular powerplant to a minimum by limiting such bypass releases to only those periods in which they appear essential to other functions of the reservoir system. Many modifications of detailed regulating criteria are possible which may - or may not - enhance the power function.

5. Municipal water supply and water quality control. Releases from each project are always maintained at or above minimum levels which satisfy these functions.

6. Recreation, fish and wildlife. Regulating criteria for the three smaller downstream projects are such as to enhance recreational use of the reservoir areas. In the large upstream projects, little can be done for the recreation function other than the maintenance of relatively balanced storage so that all of these projects share in undesirably high or low pool levels when they occur. Specific procedures for fisheries enhancement have not been incorporated into the program.

7. Extended drought period service. The large amount of carryover multiple-use space was provided to sustain water use functions through an extended drought period. The Missouri Basin drought of the 1930's, during which 12 successive years of well below normal inflows to the system occurred, was the most severe drought experienced during the historical record and as such has resulted in what may be called the design condition for reduction of service to water use functions. Criteria are established so that reductions in service will be in logical succession and of a degree which will result in this carryover space being essentially evacuated at the end of the 1930 drought.

The most recent usage of the developed program was in connection with the Missouri River Basin Comprehensive Framework Study. Studies were made for the expected 1970-, 1980-, 2000- and 2020-levels of basin development, during which period streamflow depletions in the basin increased by almost 20 million acre-feet annually. In addition to indicating the effects of increased development upon the main stem reservoir system, these regulation studies served the purpose of integrating the development effects within eight major subbasins upon the main stem of the Missouri River throughout its length.

Further development of the current program is contemplated as time and work load permit as follows:

1. The development of reasonable and consistent inflows to each reach of the Missouri River, as previously mentioned, is currently under investigation. With their development, it will be possible to synthesize inflows and thereby examine many more years of operation than given by the historical record. However, in this connection it should be recognized that the synthesis of these flows will require a consistent synthesis of the depletions or adjustments to these flows which will represent the effects of basin development.

2. An obvious solution to the problem of determining basin development effects upon reach inflows is to extend the detailed model incorporated in the current program from the main stem of the Missouri River into the tributary areas of the basin. Tributary reservoirs, irrigation projects, soil conservation practices, ground-water withdrawal effects and other depleting effects would be modeled where they actually occur, and in this manner the effects on the main stem could be determined. With the availability of high-speed computers of large capacity, a detailed extension of the model in this manner becomes practical; however, it will require a considerable amount of effort.

3. Perhaps the greatest need is the development of means to quantitatively evaluate the variations in service provided the various functions by modifications to regulation criteria. At the present time, only a general qualitative evaluation can be made, based on factors such as the average annual generation or navigation season flows maintained during a particular period. As an example, when considering the power function alone, it is recognized that the availability of peaking capability can at times be of more value than the generation of large amounts of energy. The maintenance of peaking capability requires water to be kept in storage, while energy generation requires a release of water; however, no means have been developed to give a quantitative evaluation of different regulation criteria on these factors. When criteria modifications result in variations of either item, only subjective evaluation is now possible. Many other examples could be given such as the benefit of additional flows during the navigation season, the effects of pool level variations upon the recreation function and so forth. It would appear that economic evaluations of the changes to service resulting from criteria modification is a necessary step in the definition of optimum regulation procedures. Prior to making such an evaluation, some means of defining the value of any particular service level for each of the various functions must be developed.

In summary, the analysis performed through the long-range regulation studies has been very helpful for the purposes outlined earlier in this presentation. In addition, they serve the purpose of furnishing many items of specific information relating to system functions as well as reservoir levels and releases from specific projects, together with their seasonal variations, which may be expected at current as well as projected future levels of Missouri Basin water resource development. The availability of electronic computers makes it practical to use this type of analysis to refine regulation procedures, and to give consideration to facets of basin resource development and other changing conditions as they occur. Analysis techniques are being refined as the occasion demands and the work load permits. Hopefully, they can eventually be expanded in a manner which will include a greater portion of the Missouri Basin within the "model" together with a practical means of quantitatively evaluating the effects of criteria modifications and other changes in service resulting from basin water resources development.

SUMMARY OF DISCUSSION

Compiled by H. O. Reese[1]

The advisability of optimizing operational criteria for a reservoir system, using input data that is either questionable or based on arbitrary assumptions, was questioned. Output is considered to be no better than the input used. It may be better to use available funds to improve the quality of questionable input data used in current working system simulation programs rather than to develop new programs incorporating detailed optimization techniques. Results obtained from using improved input data and current working programs may be more reliable than results obtained from new improved programs using questionable input data. Projected future demands on reservoir systems and estimates of future depletions in runoff (which are extreme in the Missouri River Basin) are examples of input data that are sometimes rather questionable. It may be that detailed studies on future demands and depletions is more important than refinement of current working system programs.

Another viewpoint was expressed that the best tools available in the field of hydrologic engineering should be used regardless of the reliability of data available for use in studies.

It was generally agreed that the above two viewpoints both have merit and should be considered in proper perspective. Factors such as available funds, objectives desired, quality of input data compared with quality of current techniques being used, should dictate which course of action is the best.

There was a question whether the operational program for the Missouri River reservoir system includes operation studies for the tributary reservoirs. Operation studies are made for all of the main stem reservoirs between the Fort Peck Reservoir in Montana and the Gavins Point Reservoir in South Dakota, but not for tributaries. These are done separately, usually be other agencies.

A discussion on use of linear programming for operation of the Missouri River reservoir system followed. Experience in linear programming in the late fifties by the Missouri River Division was discouraging. Costs were high and results were unacceptable. It is doubtfull that linear programming will be considered in the near future. It is felt now that funds and efforts should be concentrated on improving the input data being used, such as estimates and future projections of upstream future flow depletions and demands on the system. The view was expressed that linear and dynamic programming may have a place in design and planning; however, it is doubtful at the present state-of-the-art that it can be used for actual (real-time) operation of reservoir systems.

[1]Chief, Special Assistance Branch, The Hydrologic Engineering Center

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PROCEEDINGS OF A SEMINAR ON RESERVOIR SYSTEMS ANALYSIS, 4-6 NOV--ETC(U)
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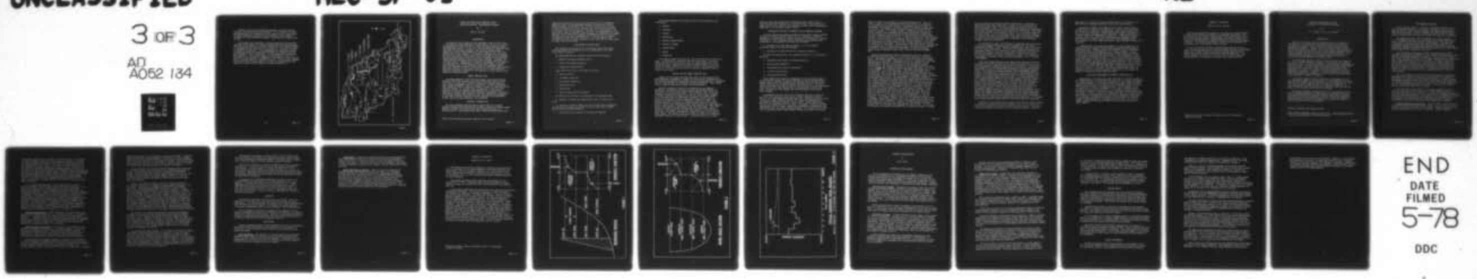

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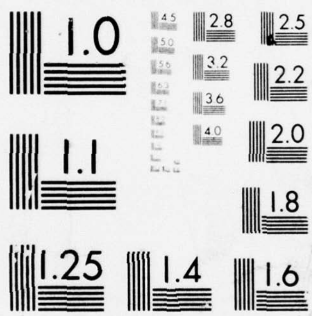
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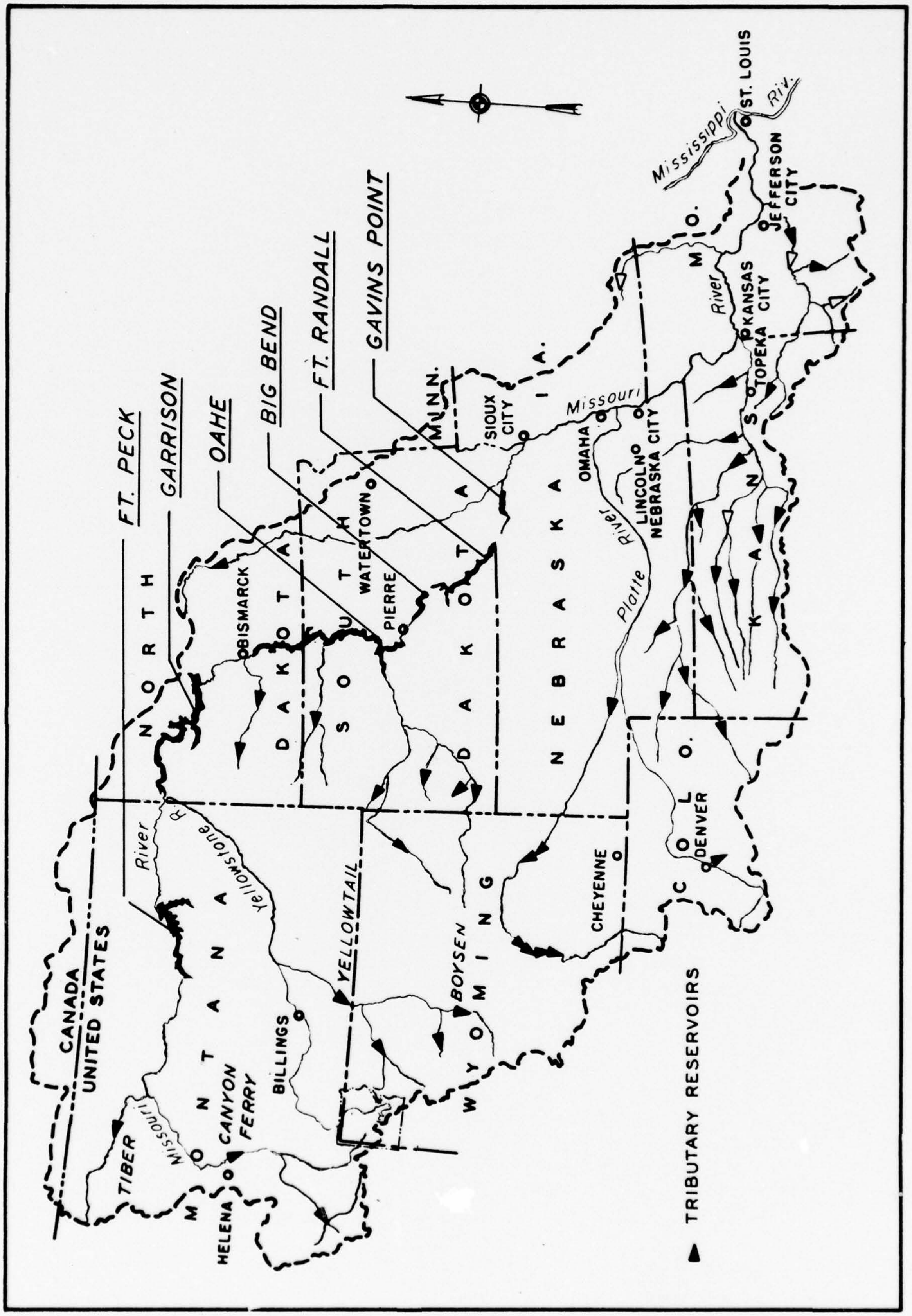
Problems connected with estimating snowmelt in making reliable forecasts of spring runoff were discussed. It is difficult to obtain good measurements of representative snow depths and water equivalents, to assess the melting process at point locations, and to analyze overland flow where drifted snow causes a retarding and storage effect on flow.

The validity and reliability of results obtained from sequential reservoir system operation studies using synthetic flows was discussed. The question was raised, are results reliable for use in design studies? It was suggested that some kind of an indicator is required to measure the degree of reliability. It was suggested that comparisons be made of results obtained from using various lengths of recorded flow from which synthetic flows are generated. In this regard the participants were referred to the current cooperative investigation by the U.S. Geological Survey and Corps of Engineers to determine the value (usefulness) of varying lengths of streamflow records. In this study, synthetic flows derived from various lengths of record are being evaluated and compared in regard to their effects on design reliability.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GARRISON
OAHE
BIG BEND
FT. RANDALL
GAVINS POINT
CANADA
UNITED STATES
TIBER
CANYON FERRY
HELENA
Missouri
River
BILLINGS
Yellowstone R.
YELLOWTAIL
BOYSEN
M O N T A N A
N O R T H D A K O T A
S O U T H D A K O T A
W Y O M I N G
N E B R A S K A
K A N S
C O L O.
M O.
I A.
MINN.
BISMARCK
PIERRE
WATERTOWN
SIOUX CITY
OMAHA
LINCOLN
NEBRASKA CITY
CHEYENNE
DENVER
Platte River
Missouri
TOPEKA
KANSAS CITY
River
JEFFERSON CITY
ST. LOUIS
Mississippi Riv.
TRIBUTARY RESERVOIRS

PLATE 1

ANNUAL AND SHORT-RANGE OPERATION PLANS
MISSOURI RIVER MAIN STEM RESERVOIR SYSTEM

By

Nels E. Carlson[1]

INTRODUCTION

The Missouri River reservoirs are sometimes called the Great Lakes of the Dakotas by proud residents of these states. This is not much of an exaggeration, since they stretch nearly the entire distance across North and South Dakota. In addition, Fort Peck Reservoir stretches about one-fourth the way across Montana. The reservoir system greatly affects the lives of people along the entire length of the river from Montana to St. Louis, Missouri. The people of Montana and the Dakotas have electric power on their farms, due in great part to the development of public hydro-electric power in the basin. Boating and fishing have become important recreation activities in the Dakotas. Irrigation of 1,500,000 acres of dryland farms is planned by pumping from the Garrison and Oahe projects. Downstream, at least as far as Omaha, the people are relatively free of the disastrous floods that destroyed homes, crops and industries along the river before the reservoirs began operation. More than 700 miles of river from Sioux City to St. Louis have been opened to commerical navigation by the operation of these reservoirs and associated navigation works.

ANNUAL OPERATING PLAN

It became apparent in 1953 when Fort Randall and Garrison started operation (Fort Peck had been in existence since 1937) that new ways would have to be devised to operate a system that affected people in such a large geographical area in so many ways. In 1953, the Missouri River Reservoir Control Center was formed to direct the operation of the reservoir system. At the same time, the governors of the ten basin states were invited to appoint representatives to a Coordinating Committee on Missouri River Main Stem Reservoir Operations. In addition, nine Federal agencies were invited to join this Coordinating Committee. In that year an Annual Operating Plan was developed by the Reservoir Control Center and was presented to the Committee.

HISTORY OF COMPUTER USE

The first operating plan was made in August 1953 and included operation studies which projected the reservoir operations 18 months ahead and also included a five-year projection of operation beyond the 18-month period. These studies were made by hand calculator methods and

[1]Chief, Power Production Section, Missouri River Division

required long tedious days of work to produce one plan of operation. Since that time, we have progressed through the agonies of using an IBM 650 computer, which took 20 to 30 minutes for one year of study. In 1961 we obtained an RCA 301 computer, which allows a one-year study to be made in two to three minutes. The results of these studies are then plotted using the automatic data plotter. The programming for these machines has all been done in machine language and therefore is not easily modified, since an expert programmer who is familiar with the program is required to make even minor revisions. It is now expected that our office will have a GE-225 computer in 1971 which will be large enough to permit the use of Fortran.

THE RESERVOIR PROGRAM MODEL

The program model describes the six-reservoir system and allows operation studies to be made for up to 16 timeperiods of four days to one month in duration.

The model describes the reservoir system with the following:

a. Reservoir storage-elevation tables

b. Travel time between reservoirs

c. Powerplant characteristics

Input data to the model is provided as follows:

a. Natural inflows

b. Irrigation depletions

c. Agricultural depletions

d. Evaporation data

e. Time periods

f. Base of flood control elevations

The control of this model is accomplished in alternative ways.

a. Reservoir releases may be specified for all or part of the study.

b. Desired or target storages for each reservoir may be specified at critical time periods and at the end of the study, with releases made to follow a specified pattern.

c. Constraints may be applied on storage and releases.

The program computes the following values for each reservoir and time period.

a. Storage

b. Elevation

c. Release

d. Evaporation

e. Channel storage effects

f. Change in storage

g. Average power

h. Energy

i. Capability

The program totals all values for each time period and for the total study. No optimization techniques are used in the model. The model allows flexibility in operation in order to permit exploration of any conceivable plan. Sensitivity analysis is employed easily, since any one of the control factors can be varied at will. The studies are of a cut-and-try nature, and from one to ten tries are required in order to obtain a final study.

STUDIES FOR THE ANNUAL OPERATION PLAN

Studies for the Annual Operating Plan (AOP) for the Missouri River Stem Reservoirs are prepared in August of each year for consideration by the Coordinating Committee on Missouri River Main Stem Reservoir Operations and for broad guidance in subsequent reservoir operations. These studies project reservoir operations through the following year.

Reservoir inflows for the AOP are determined by two separate procedures. Forecasted inflows and selected percentages thereof are used during the period from August through February, when inflows are generally low and relatively stable. At the time the AOP is prepared in August, forecasts of reservoir inflows for March through December of the following year are unreliable; therefore, inflows for this period are obtained by a simple statistical analysis of annual and monthly flows for the period of streamflow record since 1898. This analysis consists of ranking the natural annual flows of the Missouri River at Sioux City in descending order, and selecting the Upper Quartile, Median, Lower Quartile, and Adverse years from this array. These four studies are based on the four actual years of record which rank as described. The Adverse year has about one chance in ten of occurring. These studies are only illustrative of operation under a wide range of water supply. The Adverse study also serves as a basis for determining dependable capacity for power sales. A five-year extension of these

studies is made with repetition of Median and Lower Quartile years. Following each Lower Quartile year, an Adverse year is also shown which again serves as the criterion for marketing of power, based on generating capability at the reduced reservoir levels.

SHORT-RANGE ANALYSES TO DETERMINE ACTUAL RESERVOIR RELEASES

As actual operations progress through the AOP period, updated analyses are made on seasonal, monthly, weekly or daily intervals, as may be appropriate, to recognize the actual contents of the reservoirs, changing forecasts of inflow, changing release requirements and changing power requirements. The analysis is divided into two areas.

a. Releases to be made from the system, i.e., the lowermost reservoirs, Gavins Point and Fort Randall.

b. Releases to be made from the four upstream reservoirs.

Releases from Gavins Point, the lowermost reservoir of the system are based on:

a. Navigation flow targets at downstream points.

b. Flood storage evacuation.

c. Downstream flood control requirements.

d. Ice cover restrictions.

e. System storage levels.

These releases are generally independent of the internal regulation of the reservoir system, but may be dependent on system storage levels. Minimum target flows for navigation are committee for a year ahead with targets increased if increased reservoir storage warrants. The short-range studies generally consider Gavins Point releases as given requirements which must be met. Since Gavins Point is essentially a run-of-river plant, releases from Fort Randall are directly related to the Gavins Point releases.

Considerable latitude exists in the releases that can be made from the other four reservoirs, since three of these reservoirs and Fort Randall have large carryover storage capacities. Experience has shown that the greatest annual power revenue can be obtained by generating as much power as possible during the winter period. Winter generation is restricted by downstream river ice cover. Therefore, in order to produce maximum power in this season, operations are geared to releasing the maximum amount under ice without causing flooding. The reservoirs must also be at or below the base of flood control levels at the end of the winter

period in order to be available for storing spring floods. This, in effect, results in establishing target storage levels to be reached by the beginning of the winter period. The problems then boils down to determining the releases to be made to reach these target storage levels in the fall. The release levels selected depend on the state of the reservoir system, i.e., storage content, the expected inflow into the system, desired power generation and storage and release constraints. A release schedule can be devised which will maximize the total energy produced during the period of study. A release schedule with this objective results in extreme variation in releases from the reservoirs, high releases for a portion of the period, followed by very low releases or vice versa. The total amount of energy gained by this extreme variation in releases is generally not very great. Alternatively, relatively uniform releases can be considered for the entire period of time. Some variation in releases from month to month is generally advantageous to achieving maximum power revenue by generating power when it can be sold at the highest rate.

Surplus power available during the navigation season is marketed as short-term committed sales at 4 mills/kwh or above or at dump power rates. Dump power is generally sold to a specified floor price varying from 1.1 to 3.8 mills/kwh. Dump power is sold to customers who have their own generating facilities, and these sales can be curtailed without advance notice, and sold at 85 percent of the decremental savings that accrues to the customer because he is not generating his own power. If the customer has a high-cost generating plant, dump power will be sold to the customer at a high dump price. The highest dump power rate is 3.5 mills/kwh. One of the new lignite plants in North Dakota has an extremely low fuel cost and qualifies for purchasing dump power at about 1.1 mills/knh. This floor price is changed as necessary in order to achieve desired generation levels. The large amount of reservoir storage in the Missouri System allows large variation in power generation from day to day. With a particular reservoir state and target state at the end of the navigation season, the energy production for the intervening period can be determined for any water supply condition. In order to achieve the maximum revenue for this energy, it would be desirable to set the dump price floor that disposes of the total amount of energy. If the amount of this energy were known in advance and the floor price that would be required to sell this amount of energy were also known, the power revenue for this period of time would be maximized. In actual operation, the amount of energy and the resulting price can only be estimated. In the early summer of 1969, with record-high storage levels, it appeared likely that the power that could be produced would exceed the amount that could be marketed. However, the USBR was able to make short-term commitments to serve loads resulting from maintenance and forced outages, and no powerplants were bypassed for lack of load. In the last three months, dry conditions developed which reduced the supply of energy

from the reservoir system below earlier expectations. Consequently, dump power prices were raised from 1.1 mills to 3.0 mills per kwh to reduce total power load. If both the supply and load conditions had been foreseeable, it might have been possible to maintain an intermediate price floor of about 2.5 mills/kwh during most of the period. This would have substituted the sale of power in the 2.5 to 3.0 mills/kwh range for the sales in the 1.1 to 2.5 mills/kwh range. This would have increased the price of this block of power about 1 mill/kwh and increased revenue by about $3,000 to $5,000 per day for 60 days for a total increased revenue of $180,000 to $300,000.

To complicate the power load situation, commitments that can be made to serve maintenance and forced outage requirements are not easily determined in advance. Also, weather and weekly power load cycles affect the total load on the system. In spite of all these variations and unpredictable factors, it is essential to update generation estimates and forecast power market conditions continually. Since the Corps does not directly market this power, information relative to the prospective power market is obtained through the marketing agency, the U.S. Bureau of Reclamation.

After the estimated generation and market conditions are reconciled to a dump price level and other direct functions are satisfied, the undesirable reservoir operating effects must be considered. In some cases, the combination of fluctuating committed loads along with varying dump power loads results in wide release variations or undesirable reservoir levels. The acceptable release variation or the acceptable range of reservoir elevations is not always well defined. The meandering river channel can in some cases cause unpredictable irrigation pumping difficulties, as releases change from day to day. It is often possible to shift loading between plants so as to avoid excessive release variations at a sensitive location. Or if this is not possible, the dump power price criteria may be changed so as to avoid the excessive variation in release, with consequent loss of power revenue. The loss of power revenue must then be compared with the difficulties that result from this operating policy. It is difficult to place dollar values on undesirable release variations or unsatisfactory pool elevations. North Dakota, for example, has passed resolutions in their State Legislature asking that uniform releases be maintained from the Garrison Reservoir, because they feel that this will lessen bank erosion below that project. To follow their request would greatly reduce power revenues. To the extent that revenues are not greatly affected, uniform releases are maintained.

Similarly, South Dakotans have requested that the Fort Randall drawdown be eliminated or delayed as long as possible in the fall to shorten the duration of unsightly mud flats during the recreation season. This drawdown can be delayed the longest by selling greater amounts of low-price

dump power in the early fall and eliminating sale of dump power in the late fall with consequent reduction in the total power revenue.

Operations to enhance fish spawning often require special manipulations of both release and storage levels. These special operations are scheduled if they can be accomplished without undue disruption of service to other functions. Power revenues are sometimes sacrificed to a limited degree to accomplish this objective. Last spring steady or slightly rising pool levels were scheduled and accomplished at Oahe, Big Bend and Fort Randall during the northern pike spawning period. The northern pike do not spawn successfully unless inundated vegetation is available.

In making studies of reservoir operation, it would appear that the function for which benefits are most easily measured and evaluated is power production. However, overall power benefits are not necessarily the greatest with the greatest amount of energy production. In the Missouri River main stem reservoir system, overall energy production is sacrificed by drawing down Fort Randall in the fall months in order to increase winter energy production. Since energy produced during the winter period can be sold at rates 1 to 2 mills above the rates received during the summer, the lesser overall energy production results in about $300,000 worth of additional power revenue for the year. This is also true at Fort Peck and Garrison, where high releases are maintained during the winter period when the head available is somewhat lower than it is earlier in the year. Similarly, the excess power produced during the summer period will return the greatest revenue when it is possible to maintain a relatively uniform dump price base.

PLANS FOR IMPROVEMENT OF RESERVOIR SYSTEM ANALYSIS

Improvement in the system model and techniques to utilize the model for system analysis are being made coincident with the planned procurement of a larger computer. The existing program has a great number of superfluous alternatives that were utilized in multi-annual studies now being handled more efficiently by another program. The RCA 301 has not had the capability of allowing programming to be done in FORTRAN without excessive chaining and running time. It is planned to program a model and utilize a variety of selective control techniques for different types of studies. It may be possible to commensurate some of the power and non-power benefits or liabilities utilizing linear programming optimization. It is expected that sensitivity analysis will continue to be the most valuable system engineering technique utilized in that the effect of changed operating policy can be observed and the policy optimized by human judgment.

SUMMARY OF DISCUSSION

Compiled by E.F. Hawkins[1]

There was considerable discussion of the effects of runoff forecast on power operations and the losses due to imperfect forecasting. It was pointed out that future revenues cannot be estimated very precisely. In the case discussed, where revenues might have been increased, the decisions were made based on forecasted inflow and expected power market conditions. The changed power market conditions were responsible for the greater part of the change in dump criteria.

It was also pointed out that hydropower generation must often be curtailed when the power market is most favorable, because no unnecessary chance can be taken by reducing carry-over storage below required amounts and possibly thereby incurring a power shortage later. The optimum operation for power is not simply that which yields maximum power generation, but depends on load and market characteristics.

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OPERATING RESERVOIRS IN SYSTEM
SIMULATION BY AN ITERATIVE TECHNIQUE

By

P.L. Manley[1] and D.I. Hellstrom[2]

INTRODUCTION

Many of the problems confronting engineers can be classified as deterministic, i.e., given the necessary data about the problem it is possible to determine the one and only solution by use of proper mathematical equations. However, reservoir system analysis problems are not deterministic in nature. Due to very complex interrelationships between the many reservoir facilities, water uses and operating rules, there is usually not one but a multitude of possible solutions. It is therefore the engineer's job to analyze such system problems to derive the most satisfactory or optimum solution.

In recent years analysis of such problems has been facilitated by the use of computer simulation programs. In practically all programs developed to date, the network of reservoirs is analyzed as a mathematical simulation model. The name "mathematical simulation model" means that given pertinent input data on uses, facilities and operating rules, operation of the system is simulated by rapid execution of a series of mathematical equations. Operation is normally performed sequentially using some selected time increment, i.e., month, day, hour, and using either historic or synthetic streamflow.

Of the many computer routines employed in such programs the one most important, complex and challenging to the programmer is that which instructs the computer how the reservoirs are to be regulated. It is in this routine that the computer must be programmed to make logical decisions based on current system status, physical restraints, and the many, often conflicting, water needs in the basin.

This paper discusses a computer routine for the operation of reservoirs in system simulations originated by Mr. Hellstrom during the period 1966-1969 when he developed a computer basin model to simulate the operation of the Connecticut River basin. The current routine is partly the result of initial considerations and partly the result of experience gained during the development.

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THE ITERATIVE TECHNIQUE

In the prototype basin it is possible to properly regulate the outflow from storage reservoirs by continuous observation of the system. Each reservoir in effect receives feedback from those downstream points which it can influence, and this information together with the status of the reservoir itself determine the release to be made by the damtender.

The mathematical model could be designed in a similar fashion, i.e., to operate using daily time increments with the next day's release being a function of the previous day's system status. This approach is effective in analyses using short time increments. However, such an approach requires that programming methods be developed to determine appropriate reservoir regulation based on the system's status and to anticipate results from the actions to be taken.

Since the model is mathematical rather than physical in nature and since the mathematical equations can be solved at enormous speed in the computer, an iterative approach is possible. That is, a trial release can be made from each reservoir in the system, the results can be examined and, if not satisfactory, a new trial is made. On each new trial the outflow used on the previous test is adjusted up or down depending on the results of the previous trial, and, by adding a damping function to the trial releases, the system eventually zeroes in on the appropriate release for the given time increment. The resulting releases are then stored for that time increment, and the program proceeds to the next time increment.

Use of the iterative technique involves establishing a method for mathematically defining the adequacy of various flows or storages for each point in the system and for each time increment. An empirical rule was adopted involving a "priority function" which permits the assignment of a priority number for each point in the model. The numbers range from zero for satisfactory conditions to +9.99 for surplus flow or storage, and to -9.99 for deficient flow or storage.

Priority values for the points in the system represent a single value as a substitute for a complex set of system operating rules. If the priorities of all points are zero, the system is considered balanced, since all needs have been met. In the event that it is impossible to balance the system the mini-max principle is employed, and the program readjusts the storages in the reservoirs until the maximum absolute values of priorities for the set of points below any reservoir are a minimum.

Priority Function for Reservoirs. Figure 1 shows a reservoir profile on the left and the associated priority function on the right, with the priority value being a function of the storage. Inflection points in the function are defined by a set of six variables. CAPA(N) represents

the storage capacity of the reservoir at spillway crest. The priority for this or greater storage is +9.99, a physical constraint. Storage at CAPD(N) represents the minimum "dead pool" and priority values for this storage or less are -9.98. At no time is storage allowed to be less than CAPD(N) except during the initial filling of the reservoir. The storage at CAPB(N,M) represents the maximum storage desired in the reservoir, for many multipurpose reservoirs CAPB(N,M) can be visualized as the start of flood control storage space. Storage at CAPC(N,M) represents the minimum storage desired unless downstream needs become severe. Both CAPB(N,M) and CAPC(N,M) can be varied by month, and storage between the two has a priority of zero, indicating that any storage in this range is acceptable. Storages CAPB(N,M) and CAPC(N,M) may also be made equal if desired.

For storages above CAPB(N,M) or below CAPC(N,M) the priority function consists of a two linear segment whose inflection point is defined by the intersection of upper and lower priority variables, PRIUP(N) and PRILI(N), with the diagonal construction line shown. By appropriate selection of the six variables defining the priority function, the analyst can cause reservoirs to maintain a rigid or flexible method of operation. For example, if there is a strong need to maintain a **fairly** constant pool in a reservoir for recreation, the programmer would set CAPB(N,M) and CAPC(N,M) nearly equal at the desired storage level during the recreation season, and assign high values to PRIUP(N) and PRILI(N), e.g., +9.0 and -9.0. Conversely, for a reservoir whose prime purpose is water supply for downstream users, CAPB(N,M) and CAPC(N,M) would have considerable range in storage between them, and PRIUP(N) and PRILI(N) would be assigned low values, e.g., +2.0 and -2.0.

River Priority Function. Figure 2 shows a river cross section and its associated priority function. It is similar to that of the reservoir except that discharge rather than storage is involved. Safe channel capacity is designated CAPA(N), a flow of CAPB(N,M) represents the maximum useful flow, flows below CAPC(N,M) represent deficient flows, and CAPD(N,M) represents the "legal" minimum flow. A similar priority function was developed for hydropower projects in the system.

Reservoir Outflow Iteration. For the first trial operation of the system the storage in each reservoir is assumed unchanged. The purpose of this is to establish a system status for the program to attempt improvement in further trials. It also provides a by-product in that flows at one or more points can be stored for future printout which represents the response of the basin to the situation of no reservoirs.

On the second and subsequent iterations, storage in each reservoir is either increased or decreased depending on the status of the reservoir and all its downstream system points. The status is determined by scanning priority values of these points and detecting the one having the greatest absolute value. The sign of this priority is then used to determine

whether the reservoir is to increase or decrease its storage. A negative sign indicates that a downstream point is deficient in flow or storage - calling for a release, while a positive sign indicates excess downstream flow or storage - calling for an increase in storage. If the point having controlling priority is the reservoir itself, the sign logic is reversed - plus calling for a release and minus for increase in storage.

Having determined the direction that the storage change should have for the trial at hand, the next problem is to determine the amount of change. Several methods were tested in developing a satisfactory program - the first involved a binary search technique, the second used an expanded binary search with dynamic damping, while the third and adopted procedure involves an empirical method which has proven fast, simple and flexible.

Figure 3 illustrates a typical reservoir iterative operation. The ordinate represents the reservoir storage ranging from empty (0) to full (CAPA). The units are in month-second-feet for programming simplicity. The abscissa represents the series of trials. A value called storage change "STORCH(N)" is initially computed as 10 percent of the total storage, CAPA(N). The actual storage is shown by the solid line, while dashed lines represent the increment of storage change. For trial 1, there is no change in storage. Assuming that the first trial results in a decision to decrease storage, the storage is decreased by the value of STORCH(N). The program tests this decrease to assure that the storage does not range beyond the physical constraints, i.e., above the reservoir capacity or below zero. There is no limit on releases since most of the reservoirs involved could be emptied within one month although no such demands should ever be made. Future modifications will include a variable for this test in the form of an outlet works coefficient.

The value of the storage change remains unaltered in subsequent iterations as long as direction of movement of the reservoir remains the same. Thus in figure 3 the amount of decrease remains the same in trials 2 and 3. However, for trial 4 the test storage has become too low, so the system calls for an increase in storage. The program detects this reversal in direction and reduces the value of the storage change to 70 percent of its previous value before applying it to the storage. No further damping of the storage change is used in trial 5, since no reversal of direction is involved.

In complex river basin systems, it is possible for several tributary subsystems to have zero priorities for a series of trials while one or more other tributary systems are still attempting to reach a balance. In these cases, the allowable potential storage change for the "inactive" reservoirs continues to decrease at the rate of 90 percent of their previous value. This case is shown in trials 7, 8 and 9, figure 3. The reason for continuing this damping is to prevent an upsetting surge in the event that the active subsystems cause a change in a downstream point which is also under the control of the inactive subsystem.

The program also computes a system priority value, SYSPRI, equal to the priority of the single point having the greatest absolute value. The trial iterations are terminated whenever the system priority reaches zero or when the number of trials reaches a specified maximum.

The use of 10 percent of the total storage as the initial storage change and the use of 70 and 90 percent as the damping coefficients is arbitrary. A limited amount of testing has been done to find other values which would decrease the number of trials, but without any improvement. Undoubtedly each river basin system and the reservoirs therein have some optimum set of coefficients, and future studies may indicate how these may be determined.

In the event it is physically impossible to balance a system, the program balances priority values to the lowest absolute value. For example, in a system consisting of a set of reservoirs with a common downstream river point, it is possible for the river point to have deficient flow and the reservoirs to all have deficient storage. In this case each reservoir will end up with the same negative priority value as the river point, subject of course to any physical constraints that may be involved.

DISCUSSION

The iterative technique and related priority routines used in the Connecticut River basin model have been tested extensively and found satisfactory. The method provides the analyst with a simple understandable means for defining how the system is to regulate itself and secondly, it provides a programming means to derive reservoir operating decisions.

Use of mathematical simulation programs for the analysis of multipurpose, multireservoir systems is a relatively new technique, and improvements will be made in current methods. However, the fundamental principles utilized in developing the Connecticut River basin model should serve as a foundation upon which future investigators can build.

FUTURE NEEDS

Computer programming needs of the New England Division in the immediate future with respect to reservoir system analysis will be generally in three areas: flood regulation, water quality control and system optimization programs.

Flood Regulation. The Division is currently installing an extensive hydrologic radio reporting network which will transmit hydrologic data from 41 stations directly to an IBM 1130 computer. Considerable systems programming will be required in order that effective and useful analysis of these data can be accomplished by the computer.

Water Quality. There is an increasing need for systems programs with water temperature and pollution routines for determinaing appropriate reservoir operation to satisfy the needs of both the reservoir and downstream river reaches. Provisions were made in the Connecticut basin model for water temperatures and pollution routines; however, these have not been perfected.

System Optimization Programs. There is a need for optimization programs ranging from specific purpose types such as for developing optimum rule curves for single reservoirs to comprehensive programs for optimizing the complex operation of multipurpose reservoir systems. Although the writing of routines for optimizing tangible benefits is straightforward, mathematical results are often of academic value, due to the many intangible, physical, legal, political and sociological factors in the operation of multipurpose multireservoir systems. The development of useful general-purpose optimization programs is a challenge to both the water resource engineer and the programmer.

SUMMARY OF DISCUSSION

Compiled by D.C. Lewis[1]

The priority specification technique of reservoir system operation, which is presented in this paper, appears to have great potential for application. The use of priority functions for river flows is unique to the program being described. Conversion of other objectives, e.g., power, quality, etc., to flow priorities can permit simulated operation for any requirement.

The program simulates monthly operation and iterates for only one period at a time. A possible future development might use daily flows, with only one iteration per day, without balancing the operation each day.

A case study illustrating the application of the priority specification technique was described. Ten private reservoirs on three tributaries are operated for paper mill processing requirements. The low flows are polluted by plant effluent. To correct the situation, FWPCA is requiring primary treatment of the effluent; however, the resulting quality will still be unacceptable at downstream points. The Corps of Engineers has two flood control reservoirs under study on the tributaries. Added storage for flow augmentation is required to bring quality up to FWPCA standards. The operation of the existing private reservoirs was modeled with the program, and the model was verified. Fifty years of simulated operation with existing reservoirs operated for paper mill requirements showed no shortages at the paper plants. Addition of FWPCA flow requirements by means of the associated priorities downstream resulted in shortages at the downstream control point, because the upstream (paper mill) priorities operated the existing reservoirs for the paper mills, not for the downstream control point. In order to incorporate the tributary reservoirs and to satisfy downstream needs, a study of relative priorities of flows at the paper mills and downstream would be required.

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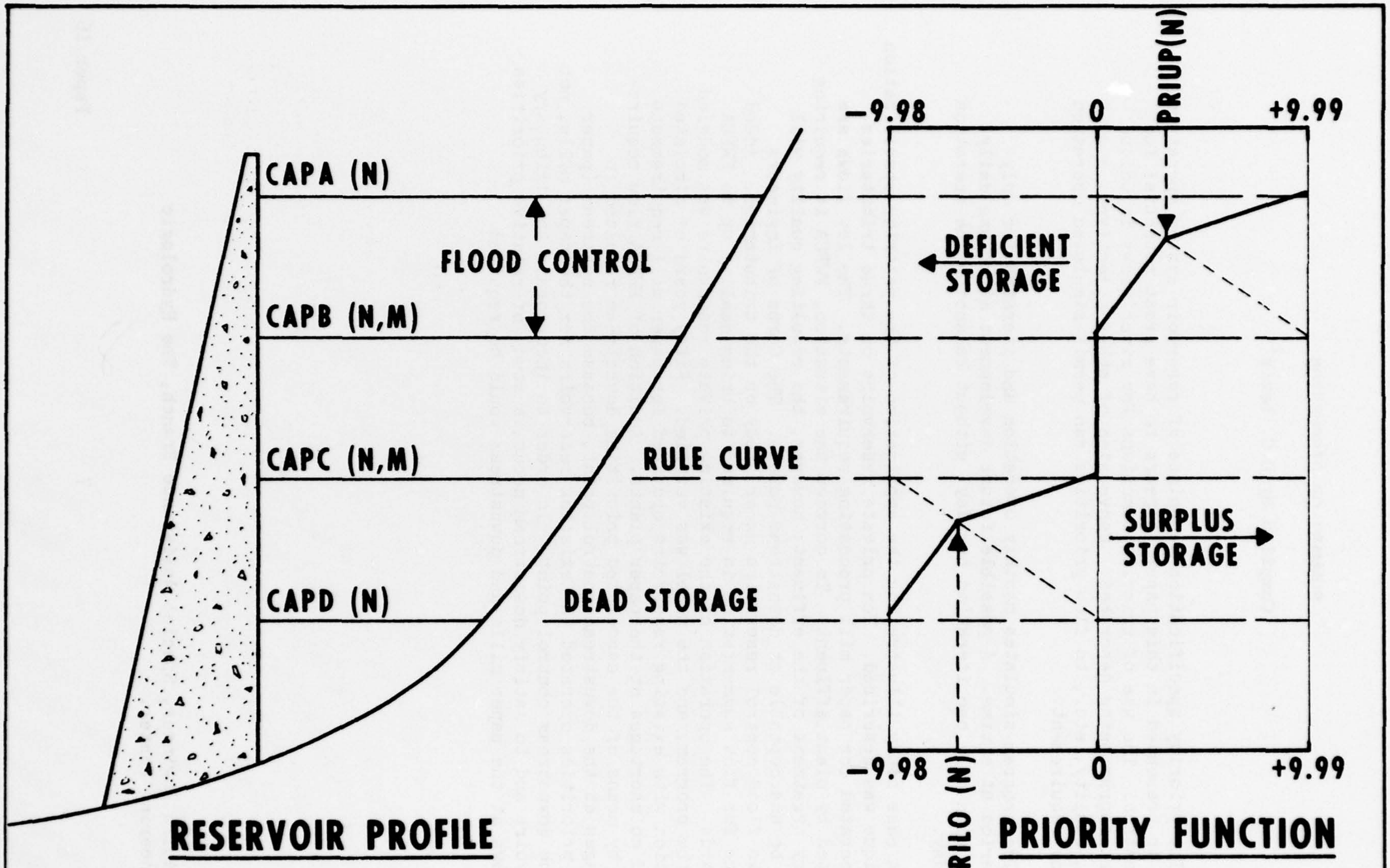
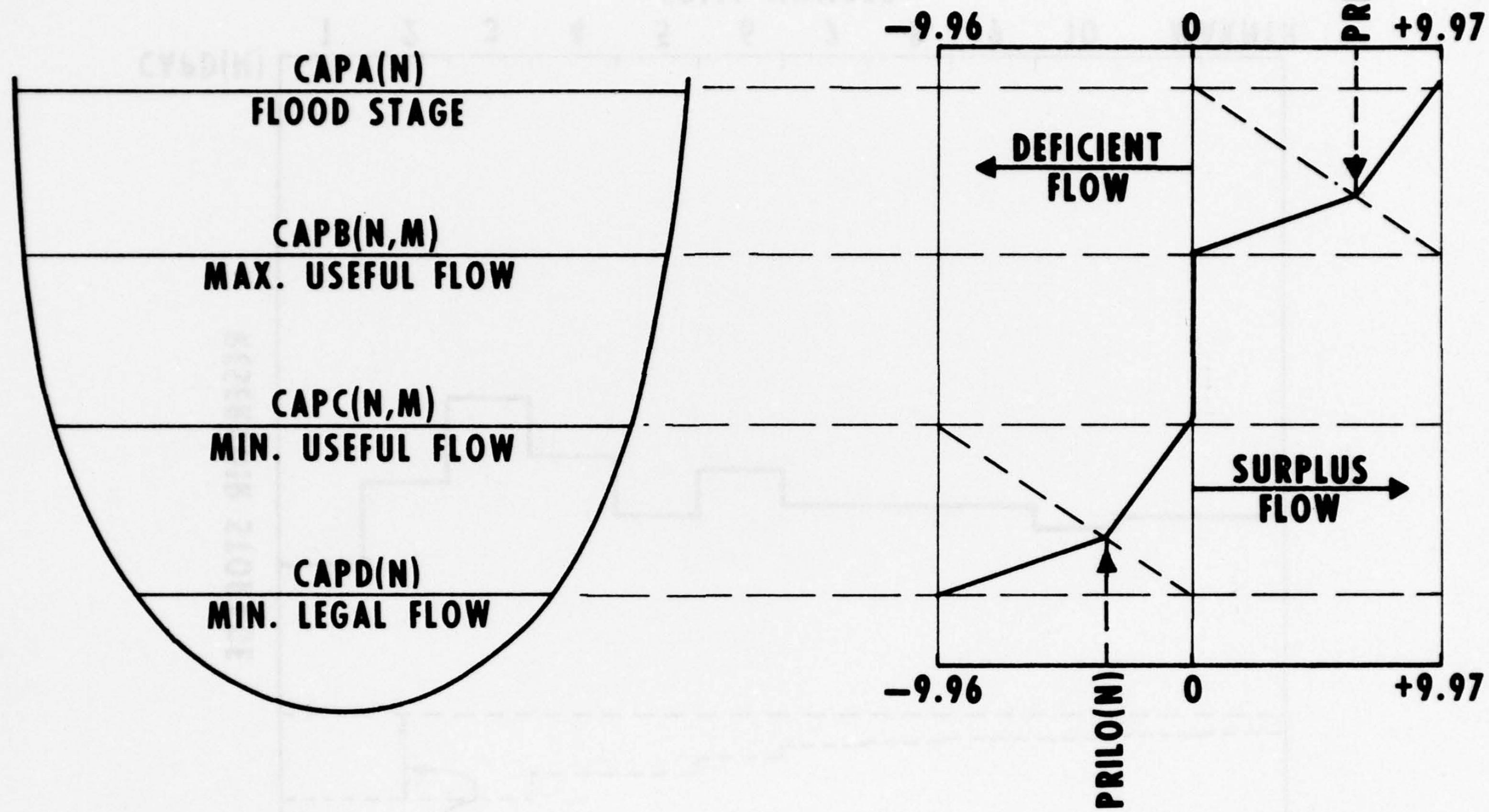

CAPA (N)
CAPB (N,M)
CAPC (N,M)
CAPD (N)
FLOOD CONTROL
RULE CURVE
DEAD STORAGE
RESERVOIR PROFILE
-9.98
0
+9.99
PRIUP(N)
DEFICIENT STORAGE
SURPLUS STORAGE
PRILO (N)
PRIORITY FUNCTION

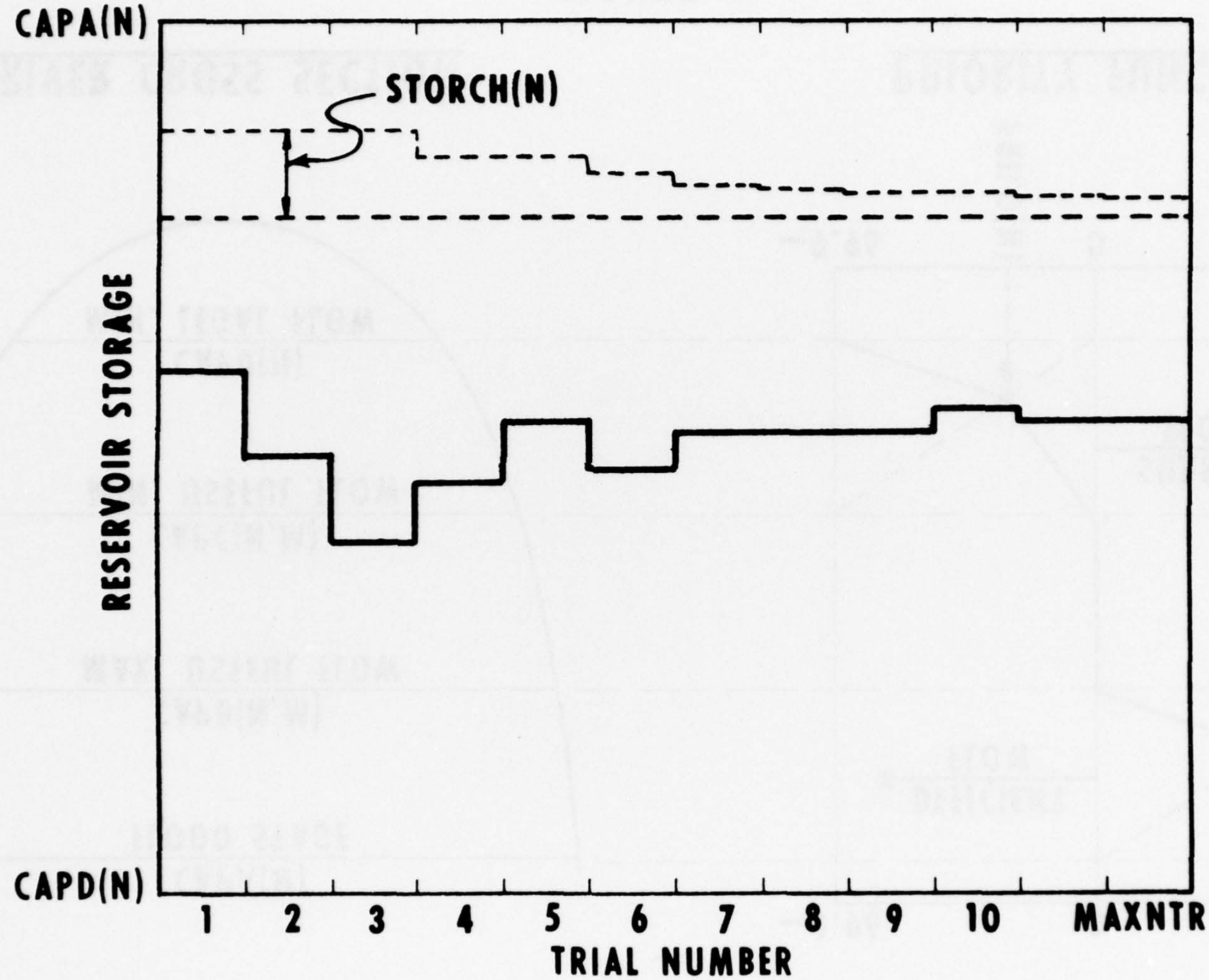
FIGURE 1



RIVER CROSS SECTION

PRIORITY FUNCTION

FIGURE 2



TYPICAL RESERVOIR TRIAL RELEASES

INITIAL STORCH(N) =0.10×CAPA(N), SEE TEXT FOR OTHERS

FIGURE 3

SUMMARY AND CONCLUSIONS

by

Leo R. Beard

RESERVOIR SYSTEM PROBLEMS

The case histories and descriptions of problems presented in this seminar are considered to be a representative sample of the reservoir system problems that exist throughout the country and of the way various projects are being planned and operated. We will not review these in this closing discussion, because they have been adequately documented. However, there are several other categories of problems that might warrant discussion.

Administrative Problems. Throughout this seminar, there were various discussions of water resources policies that were beyond the scope of the seminar, and it is not appropriate to summarize these here. However, some policies discussed are closely related to our ability to effectively cope with engineering problems. One of these is the apparent reluctance in many offices to fully document the problems, presumably because it might invite criticism. It was generally felt here that these problems should be documented to the extent that they will help others avoid problem areas in the future.

Another administrative problem discussed is the necessity to plan a part of a system in a hurry, when early authorization for the part is needed. While it is recognized that this cannot be avoided, it should also be recognized that this imposes additional constraints on the overall system.

Personality Problems. A phrase mentioned several times in this seminar is "pride of authorship". Usually there is a lot more reason for wanting to use ones own procedure than simply pride of authorship. For one thing, the engineer understands his own methods and computer programs and their limitations, and it would take him quite a while to understand others. In the case of computer programs, it is not uncommon to examine several without finding a program that suits a particular need. Perhaps the solution to effective exchange of computer programs would consist of program descriptions that demonstrate, very briefly but completely, just what the program will do and what is needed to use it.

Another personality problem that was mentioned frequently is the problem of replacing seat-of-the-pants operators. Often one man is completely familiar with a system operation, and it is necessary to transfer his knowledge and techniques into a system analysis that can be used by his successors.

Probably the most serious personality problem is failure on the part of most of us to recognize the complexity of the other fellow's problems. We often feel that our particular computer program will suit the other persons needs. However, it is usually found that each new problem has challenging new aspects.

Engineering Problems. Probably the word used most frequently in this seminar is the word "complex". One factor that adds greatly to the complexity is the fact that reservoir systems are not designed, but grow as needs for various services develop. Different units are built for different purposes. As units are built and operated, they immediately establish constraints that will control the design in future elements in the system. While many reservoir systems are operated for six or eight purposes, it is found that one or two functions are dominant. The problems discussed here at the seminar were predominantly power oriented. Fitting the hydropower into the overall power load is a complicated process. This is further complicated by the changing use of hydro in the overall marketing picture.

Water quality was mentioned quite a number of times. Dissolved oxygen was the primary consideration in these cases. However, as temperature and other quality parameters become of vital concern in reservoir operation, the complexity of the water quality analysis will surpass that of the power analysis.

Flood control is still one of the most complicated aspects of reservoir system analysis, although it was not discussed to great length in this seminar, since associated problems have been discussed at length before.

Irrigation problems also obtained little discussion. However, problems recognized in the Missouri River basin studies, where main river flows are being drastically reduced by upstream use, will also exist in other river basins. These problems are associated with the problem of adjusting historical flows to a specified level of development before they are used in system analysis.

The balancing of storage in various reservoirs, in order to assure that the system requirements at all times or locations can physically be served, has received considerable attention. It should be stressed that the balancing techniques used in The Hydrologic Engineering Center's Reservoir System Analysis Program (HEC 3) is a highly flexible system that permits a direct solution for reservoir releases. Some of the other techniques discussed require iterative solutions.

Of great concern to all here is the requirement of a high degree of fidelity in simulating reservoir system operation. In many operations, the translation and attenuation effects that occur as water travels downstream are of vital concern. The exact computation of evaporation, even

to the extent of specifying different amounts during dry years than during wet years, can be of great importance in some studies. Such items as the seasonal variation in the market value of power can greatly influence the system operation. It might be concluded, then, that any general solution to reservoir system problems must be capable of analyzing a system in great detail.

A major problem in reservoir system analysis is that of analyzing the voluminous amounts of output from a computer study and determining how the system operation should be changed in order to change the outcome in a particular way. It is important to tabulate the material in many ways, but it is also necessary to make detailed studies of the critical elements in the output. The computer can be programmed to do this.

PRESENT METHODS

The techniques that are presently used in planning and operating reservoir systems are restricted almost entirely to simulation techniques. The system operation is simulated in as much detail as is necessary for a reasonable representation. In order to improve the design or operation, logical changes in system elements and criteria are made, and the simulation process is repeated. This process is repeated until optimum results are obtained.

The simulation process is still very approximate in many respects. For example, streamflow routing effects are approximated or ignored in many studies. Also, weekly or monthly averages are often used when more detailed data might give appreciably different results.

It is necessary to use several simulation models for analyzing different aspects of a single study. Usually, conservation and flood control studies are made separately on a coordinated basis. Conservation studies are usually supplemented by some short-period more detailed studies.

Operations research and stochastic hydrology are not used to any significant extent in reservoir system analysis. Several attempts have been made to use operations research techniques. These were usually by contract with an outside organization. All of these have been judged to be of little significant value, except insofar as they encourage future development of the techniques.

FUTURE IMPROVEMENTS

Perhaps the greatest future need discussed in this seminar is the need for better definition of the objectives or the criterion to be used for optimizing a system. Some fundamental objectives such as maximum

net benefits or minimum costs are not sufficient in themselves. Some consideration of equitable distribution, intangible values, and social considerations should be included in the objective function.

There is a need for a broader treatment of the entire reservoir system analysis problem. This includes the need for better data, greater detail in the analysis, greater operation flexibility, inclusion of contingency allowances in the operation plan, and development of water quality analysis routines.

It is recognized that any system is only a part of a larger system, and there is a tendency to increase the scope of any system analysis, because there is some feedback from the larger system. While it is necessary to maintain a reasonable scope, there are cases where an increase in scope appears to be essential. For example, the inclusion of the thermal power component of the power load in a hydropower analysis appears to be essential, if optimum use of hydropower is to be obtained.

An important step in applying system analysis techniques to reservoir system problems is the preprogramming of decisions that are largely subjective in actual operation. It will be necessary to determine the rationale of these decisions and to express it mathematically, if possible.

The needs expressed for broader scope and in-depth analysis of reservoir system studies will result in the need for greater computer capability. While it is theoretically possible to use overlay and chaining techniques, and thus employ intermediate computers, it might not be feasible to do so, in view of the tremendous problem of programming and the time and cost required for computer analysis.

Methods of optimizing the design or operation of a reservoir system are seriously needed. It is only recognition of the almost insurmountable problems that de-emphasizes this need. In reviewing the problems that exist in the light of currently available operations research techniques, it appears that any practical optimization technique must be based on a logical detailed examination of the interrelationships within a system and their effects on system accomplishments. A high degree of fidelity must be maintained in simulating and analyzing the real system.

The application of stochastic processes is restricted by the lack of complete faith in the results and by the requirement of greater amounts of computation. There is a serious need to evaluate how useful stochastic hydrology really is and to demonstrate that it is dependable. In many of the discussions in this seminar, it was recognized that stochastic flucuations in demands can be as important as fluctuations in the supply.

Lastly, there is a definite need for good communication between design engineers and the academic community. The communication must be in both directions. It is incumbent upon the design engineer to describe the

problems fully for the benefit of the academic community, and to describe the techniques he is using. It would also be well for him to explain reasons for not using so-called "more advanced" techniques. Likewise, it is incumbent upon the originator or proponents of new techniques to participate in the enormous job of adapting these techniques to the complex problems faced by the design engineer.

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